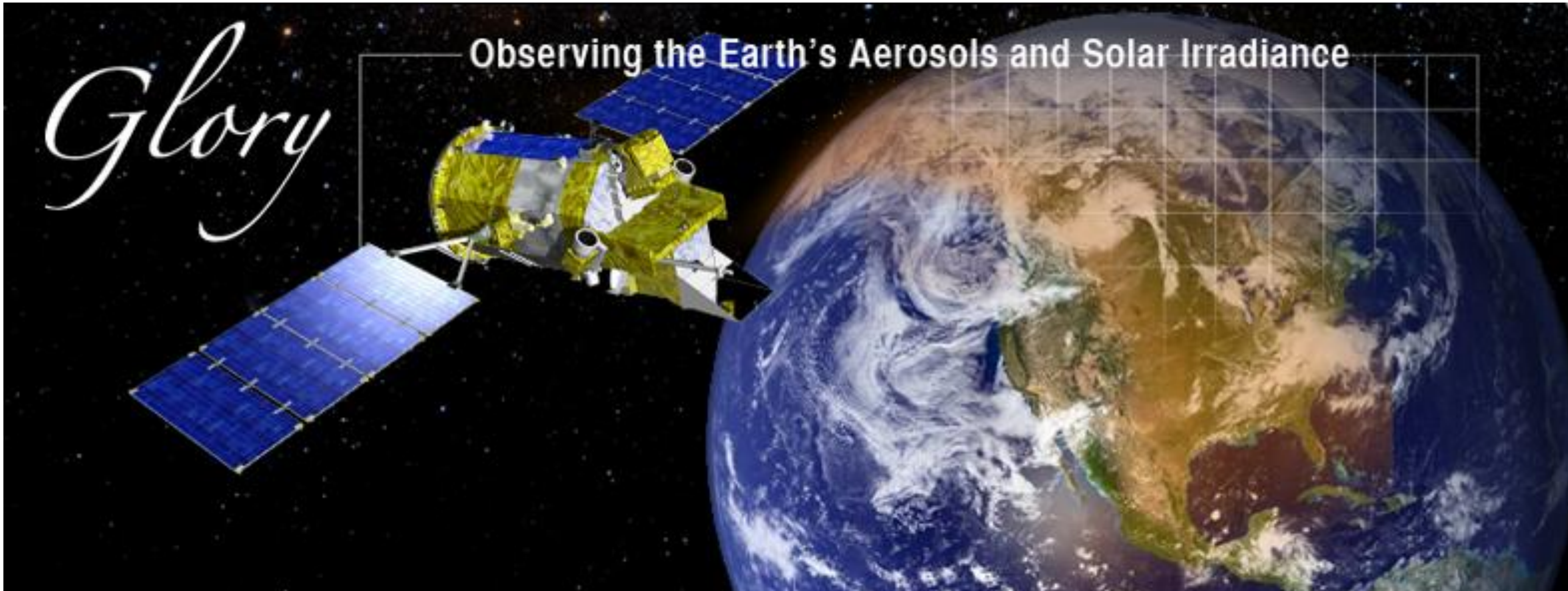

Retrieval Products from the Earth observing instruments on the Glory mission

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A-train meeting
October 2010

Overview

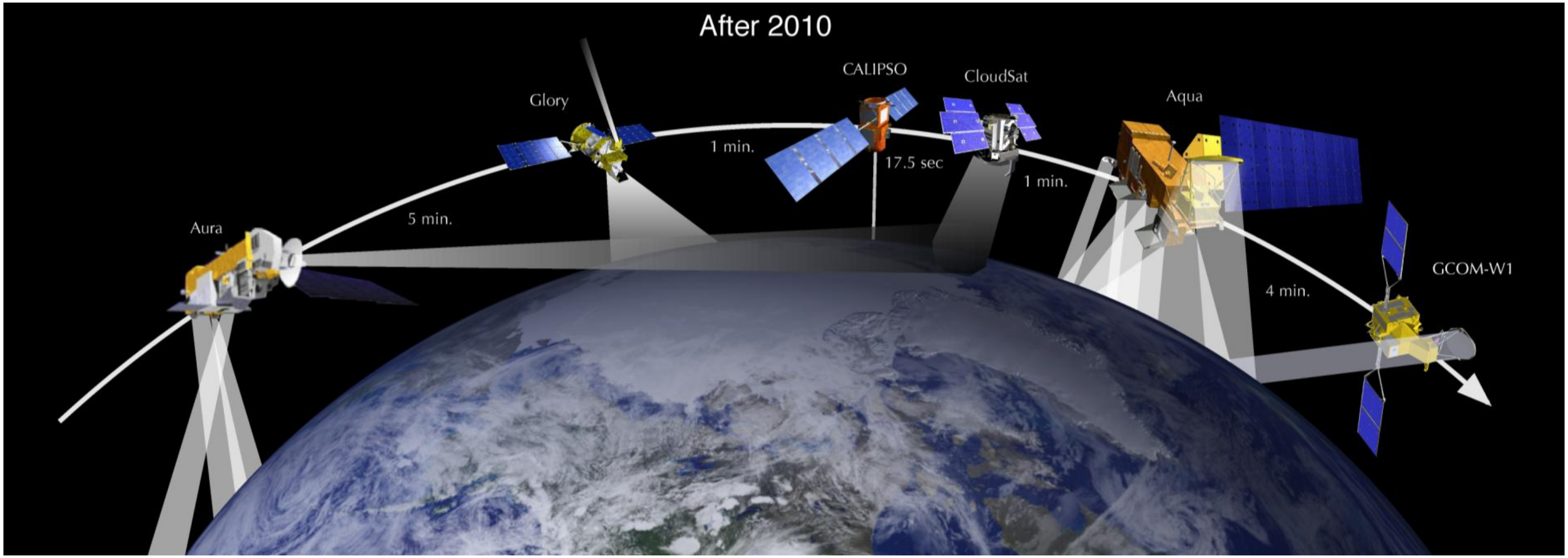
- Cloud Mask
  - MODIS
  - Cloud Cameras
  - CALIPSO
  - APS
- Water vapor
- Aerosols
  - Over the ocean
  - Over land
  - Over clouds
- Clouds
  - Ice/water
  - Land/ocean
- Surface BRDF

Cloud Mask

- Cloud Mask
  - Single mask for cloud cameras with P-values for variability, threshold and deviation from MODIS masks.
  - Single mask for APS that merges results from other masks (MODIS and cloud cameras) to provide a cloud fraction, cloud fraction uncertainty and thin cirrus screen for an APS scene that allows decisions on APS retrievals (cloud, aerosol, cloud above aerosol) to be made

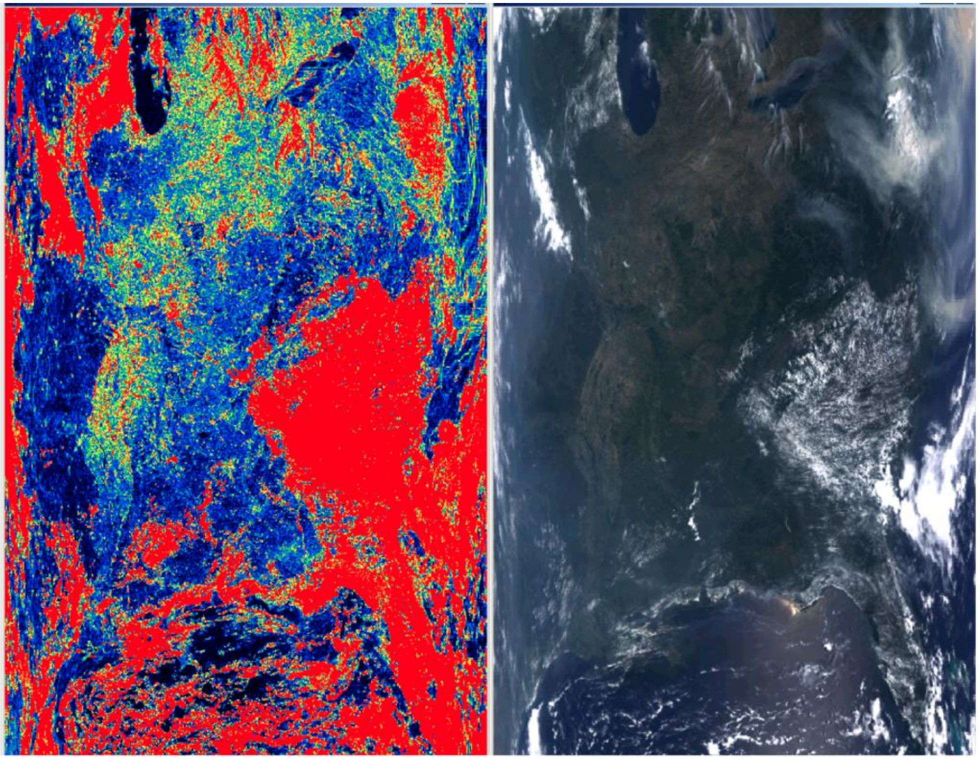
Cloud Mask

- Cloud Mask
  - APS looks ahead into the MODIS swath
  - The cloud cameras observe a part of the MODIS swath with a slightly more than 2 minute delay
    - At 3 m/s a cloud moves a complete pixel in the time between the MODIS and the CC observations.



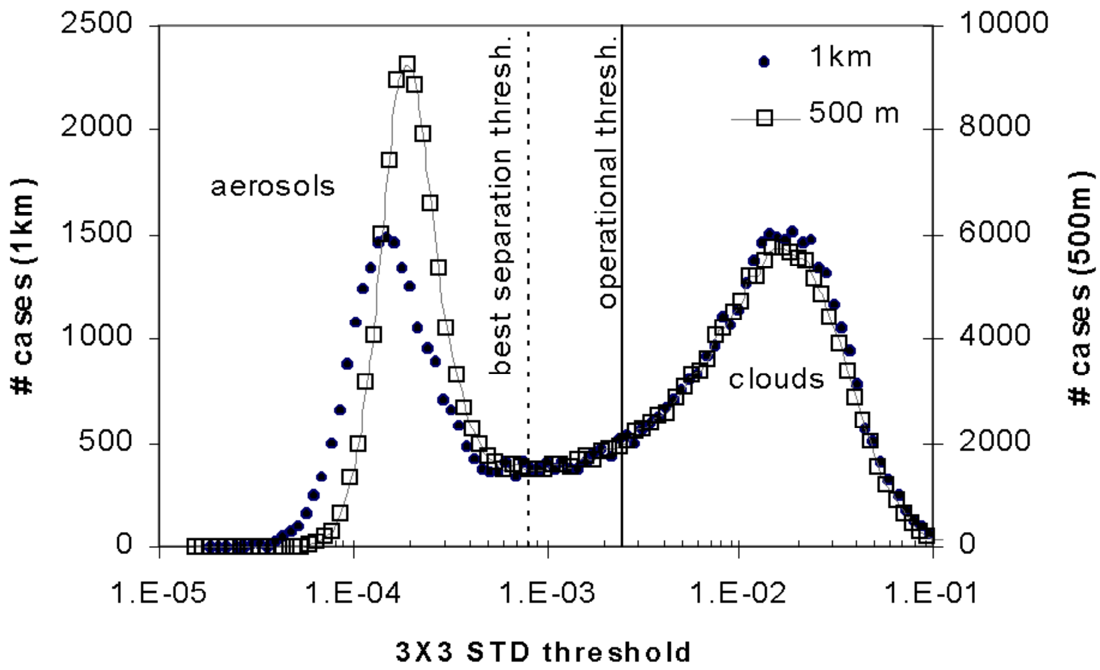
Cloud Mask

- Cloud Mask
  - MODIS (Martins, Remer, Kaufman, Koren)
    - Standard cloud mask + variability at 644/863 nm over ocean, or 470 nm (shown here) over land



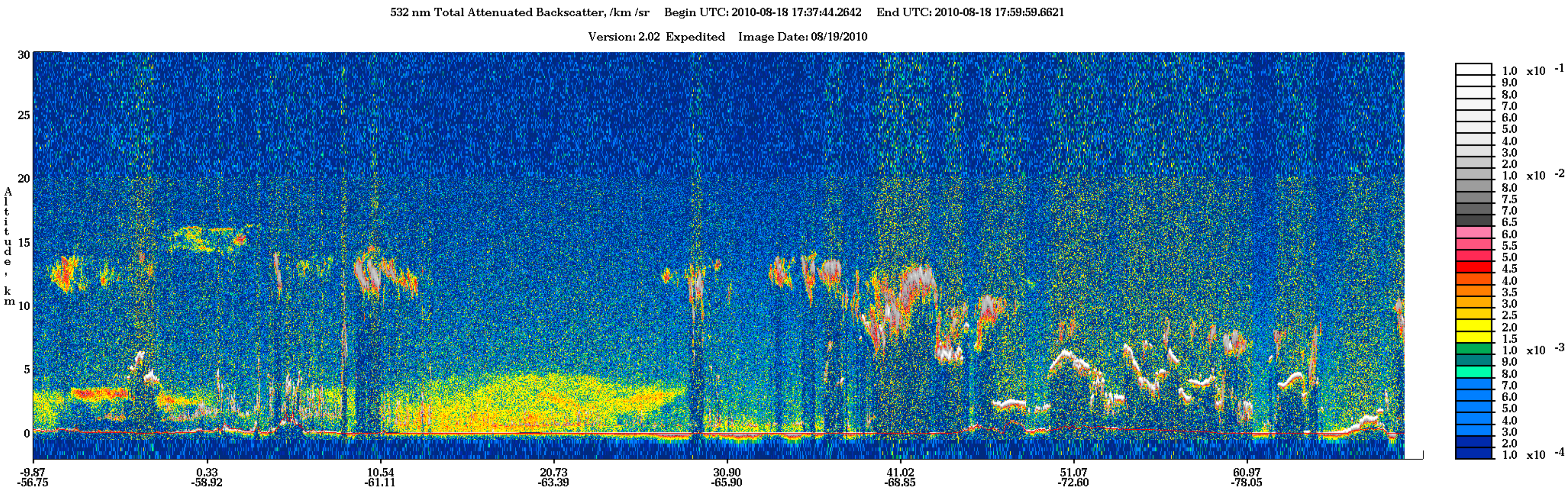
Cloud Mask

- Cloud Mask
  - Cloud Cameras
    - 865 nm over ocean and 443 nm over land
      - Variability (*cf.* figure below from Martins et al.2002) is primary mask, supplemented by radiance thresholds



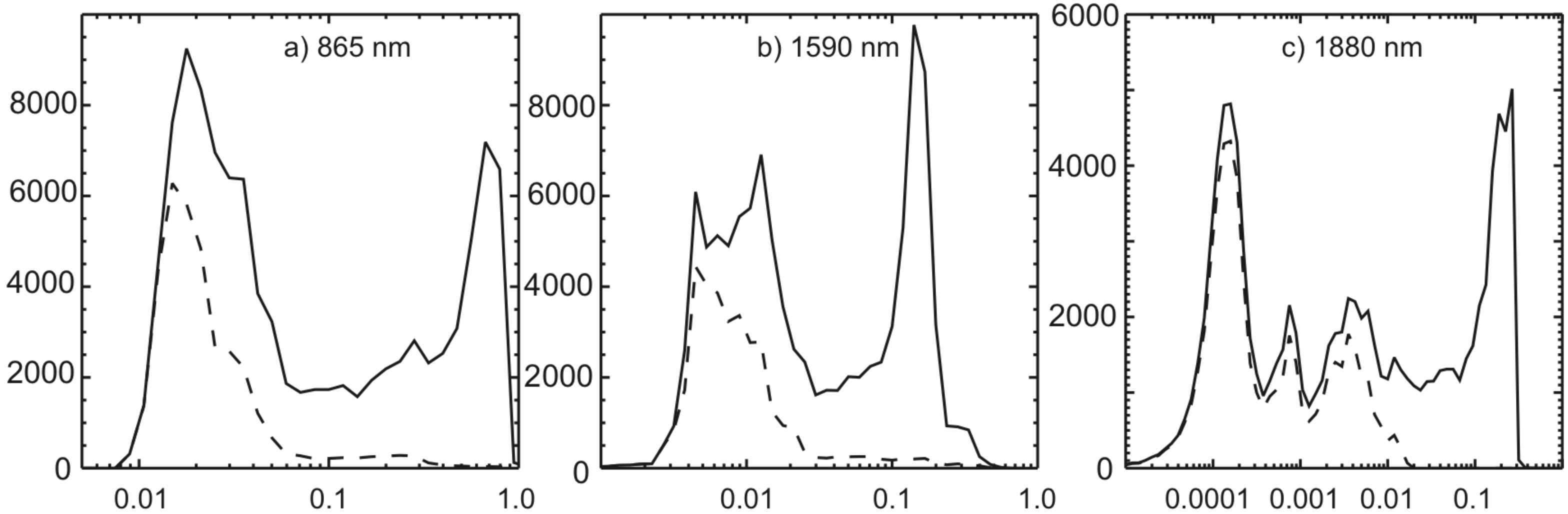
Cloud Mask

- Cloud Mask
  - CALIPSO
    - Aerosol/Cloud layer identification
    - As identified by analysis of POLDER data (*cf.* Waquet et al. *J. Atmos. Sci.* 2009) the cloud top pressure determined by polarimetric observations will be affected by aerosols above cloud



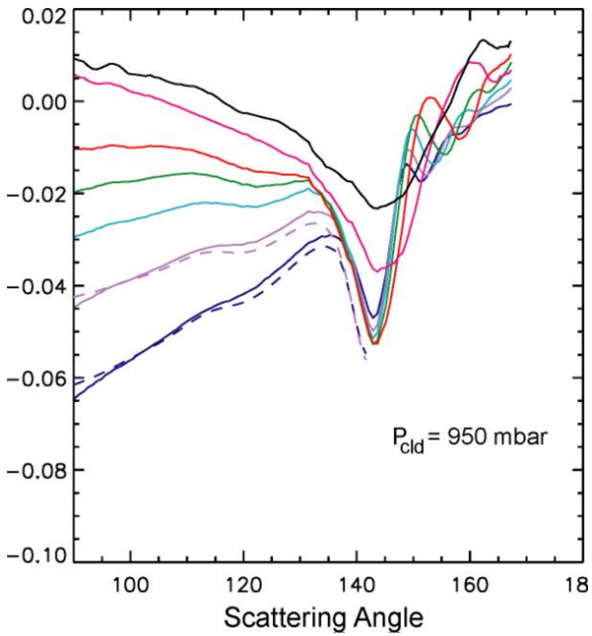
Cloud Mask

- Cloud Mask
  - APS
    - Thresholds on channels for which surface is dark
      - 865, 1610, 2250 nm over ocean
      - 410, 443 nm over land
      - 1378 nm for both land and ocean
        - Figure shows reflectance histograms. In a) and b) the dashed line has had those scenes identified as cloudy by the 1880 nm band removed. In c) the dashed line has had those scenes identified as cloudy using 865 and 1590 nm removed.



Cloud Mask

- Cloud Mask
  - APS
    - Estimate of atmospheric pressure above surface/cloud/aerosol from 410 and 443 nm polarized reflectance. Aerosol index calculated using this pressure to assist in identification of dust against ice clouds.
    - Angular variability of radiance also used to identify sub-pixel cloud.



Cloud Mask

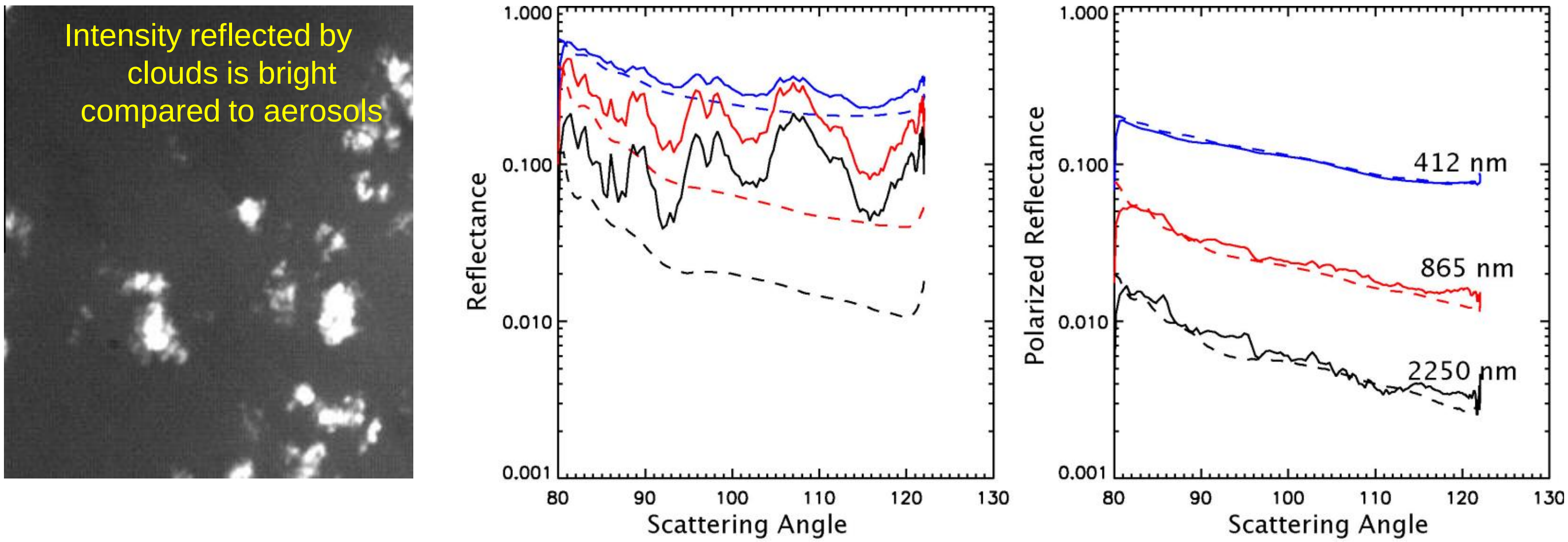
- Cloud Mask
  - Clear scene
    - Standard aerosol retrieval for appropriate underlying surface (land/water)
  - Cloudy scene
    - Relative variability is robust against absolute radiance levels and should identify thick aerosol layers as aerosols NOT clouds (Martins *et al.* 2002)
    - Radiance thresholds are more likely to classify thick aerosol layers as clouds.
    - Additional tests for differentiating between clouds and aerosols when clouds are identified by these tests are:
      - Rainbow to identify water clouds
      - Use aerosol index at 410/443 nm to differentiate color of dust aerosols from that of ice clouds

Cloud Mask

- Cloud Mask
  - Cloudy scene
    - Calculate scene cloud fraction based on revised assessment of cloud mask
    - Partially cloudy
      - APS cloud retrievals for each view separately
      - Aerosol retrieval using only polarized radiances
    - Overcast
      - Cloud top pressure agrees with CALIPSO
        - Cloud retrieval only
      - Cloud top pressure disagrees with CALIPSO
        - Aerosol above cloud retrieval
    - Sub-visible cirrus only
      - Cirrus above aerosol, cirrus contribution to scene subtracted and standard aerosol retrieval performed

Cloud Mask

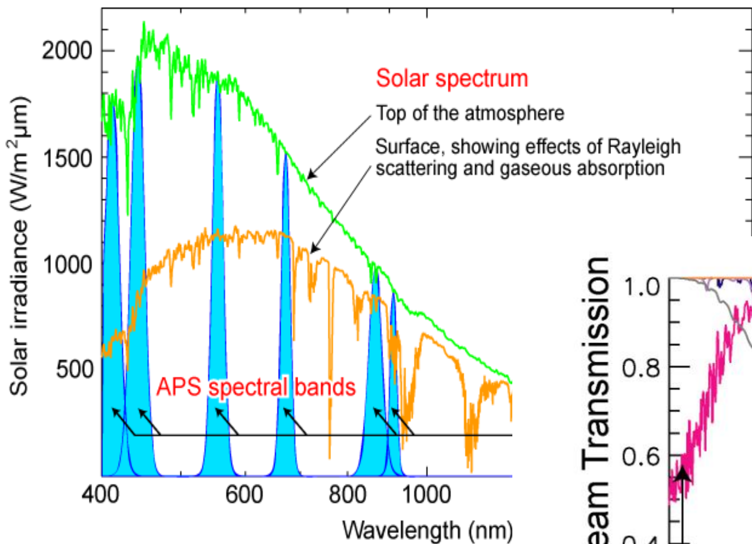
- Cloud Mask
  - Cloudy scene
    - Partially cloudy

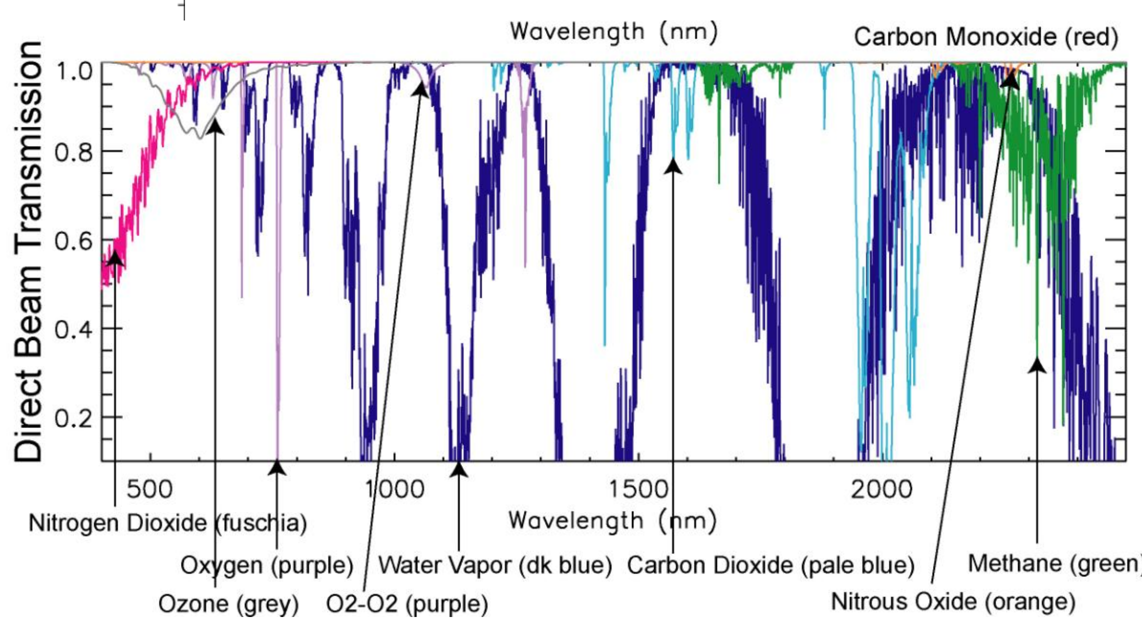


- Dashed line from clear scene, solid from broken cloud
- Away from the rainbow the polarization of clouds is small
- Clouds are black! - polarimetrically speaking.

Water Vapor

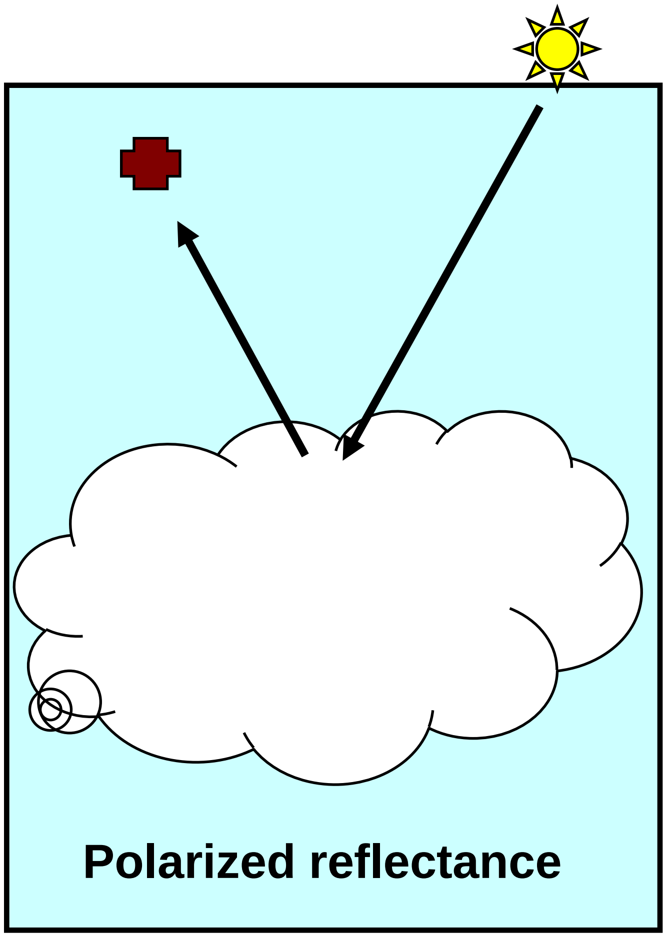
- Product is total column water vapor that can be used to correct weak water vapor continuum absorption at 1.61 and 2.25 µm.
- Observations at 910 nm and 863 nm use a method similar to that of Gao et al. for MODIS water vapor.
  - Worst accuracy over oceans where surface is dark

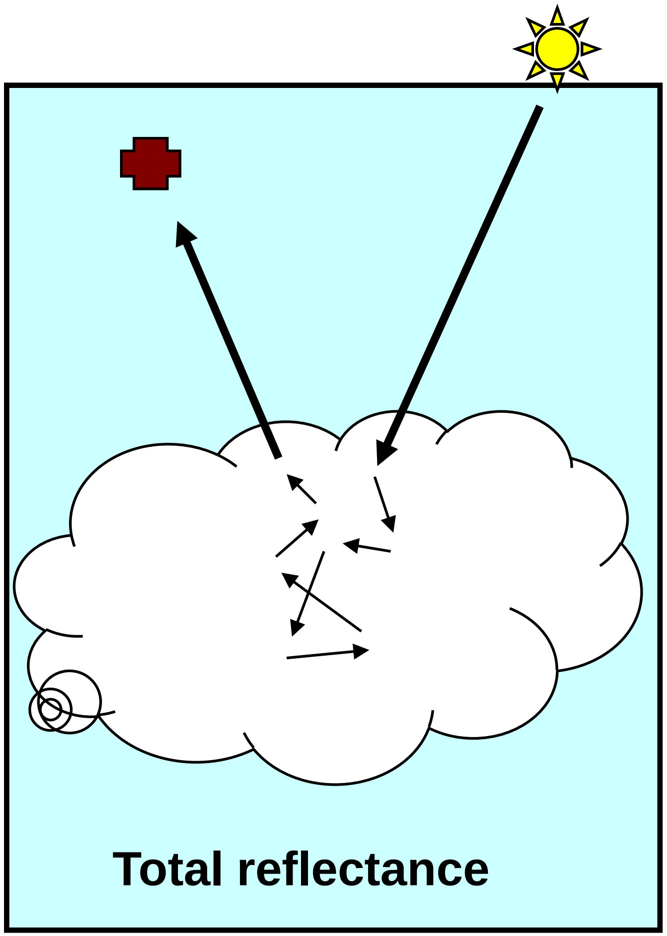




Water Vapor

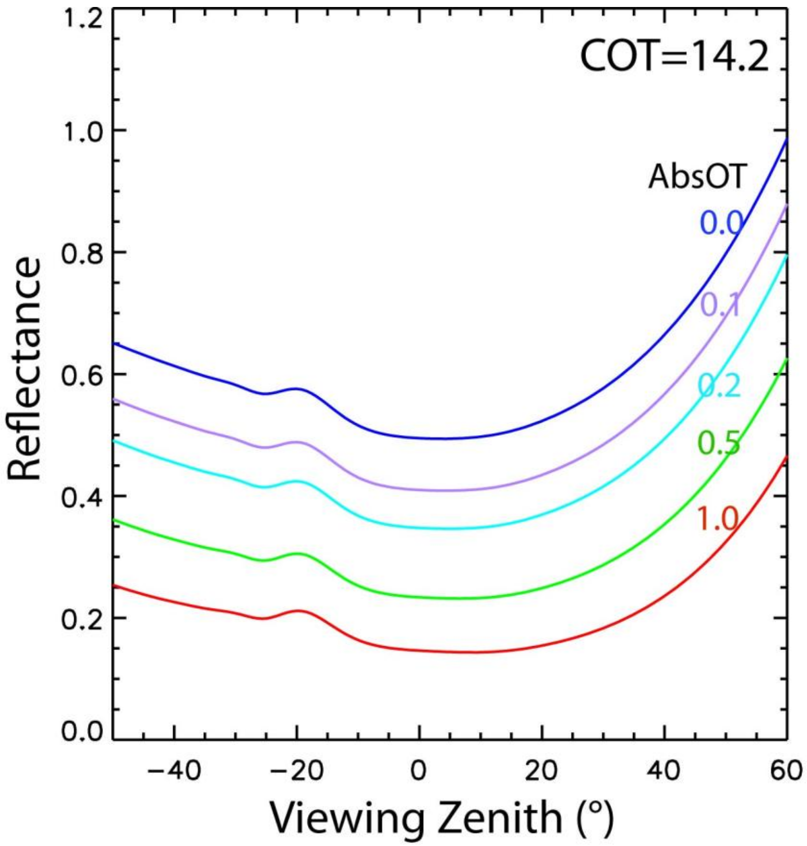
- Polarized and total reflectance path lengths differ for clouds

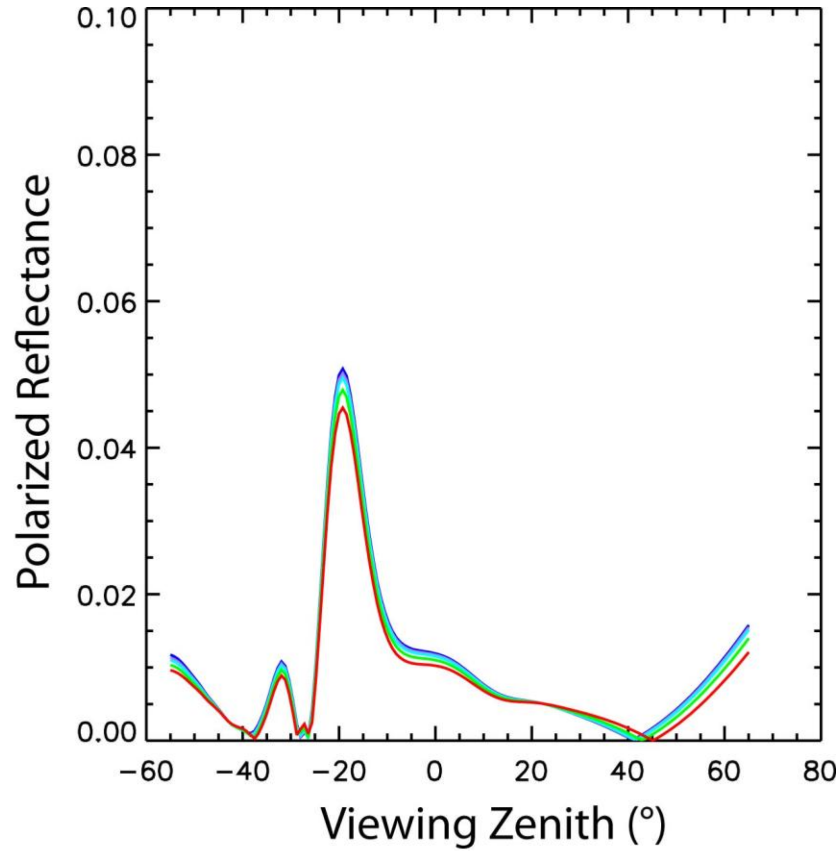




Water Vapor

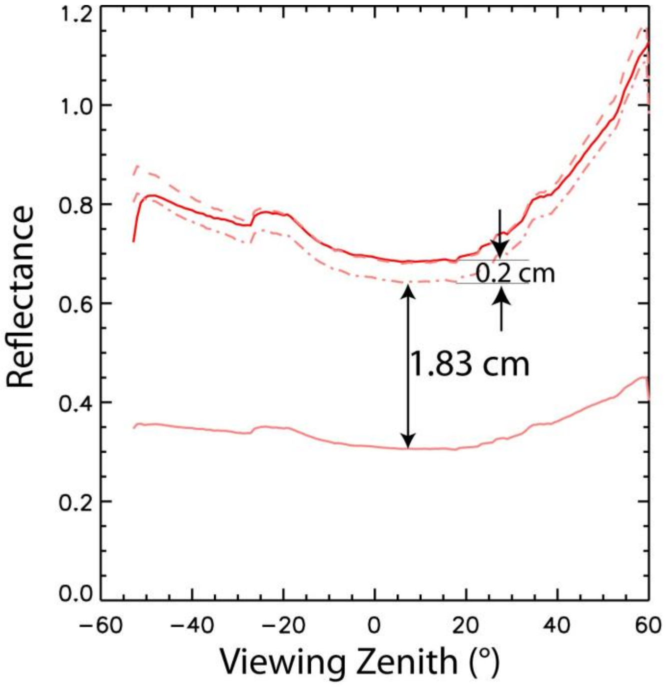
- This means that the cloud absorption optical thickness changes total reflectance but has little effect on polarized reflectance.
- Polarized reflectance in a band where water vapor absorbs depends on the vapor above the cloud.

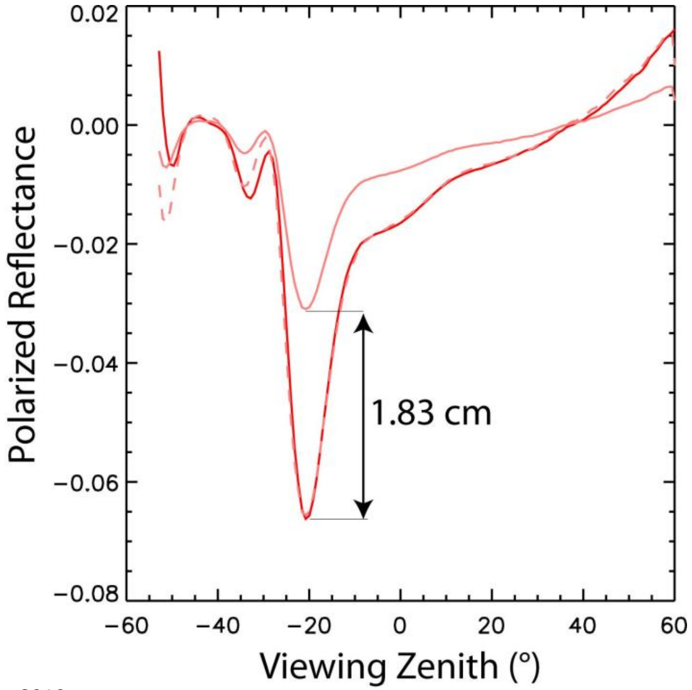




Water Vapor

- Polarized reflectance generated near cloud top, whereas reflectance generated throughout atmospheric column. In stratocumulus example shown here:
  - The water vapor estimate of 1.83 cm from polarized reflectance is for absorption above cloud.
  - Additional 0.2 cm for reflectance is for water vapor inside cloud.
  - The additional absorption in the total reflectance observations provides a measure of multi-layer/cloud extent analogous to that used in the MODIS multi-layer detection method (Joiner *et al.* 2010, Wind *et al.* 2010)



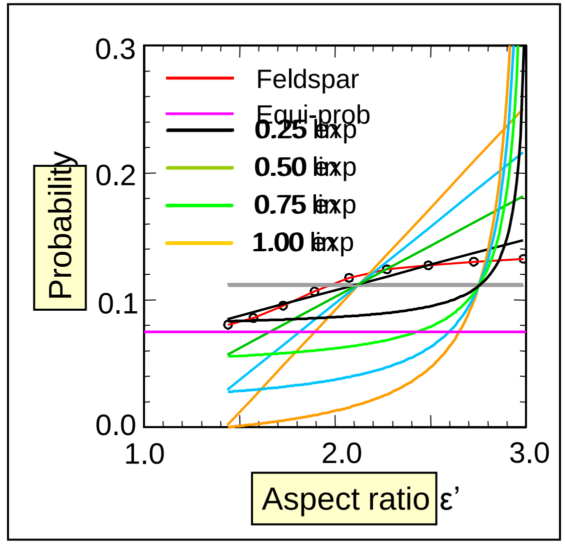


Aerosols

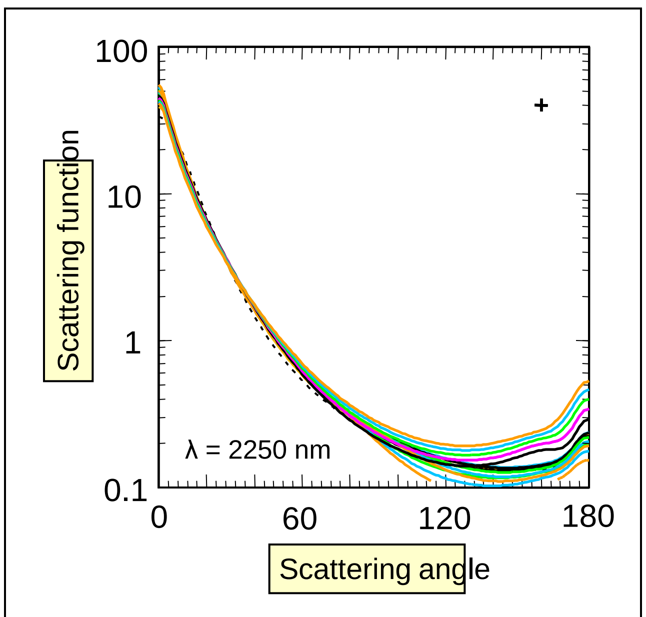
- Aerosols
  - Two aerosol modes. For each mode the following are retrieval products:
    - Optical Depth at a reference wavelength of 555 nm
    - Effective radius and variance
    - Spectral real and imaginary index
      - Real indices are parameterized as a value and a slope
      - Imaginary indices are parameterized as a constant (black) contribution and a “brown” contribution derived from laboratory measurements. Dust is also parameterized as a spectral shape with variation in magnitude of that shape function.
    - Shape: if residuals indicate spherical model is not acceptable a dust model is used
  - Derived products at 410, 443, 555, 673, 865, 1610 and 2250 nm are:
    - Spectral optical depth
    - Spectral single scattering albedo
    - Spectral asymmetry parameter

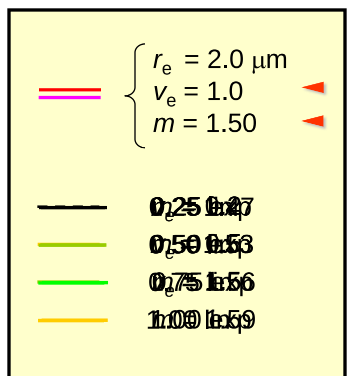
Aerosols

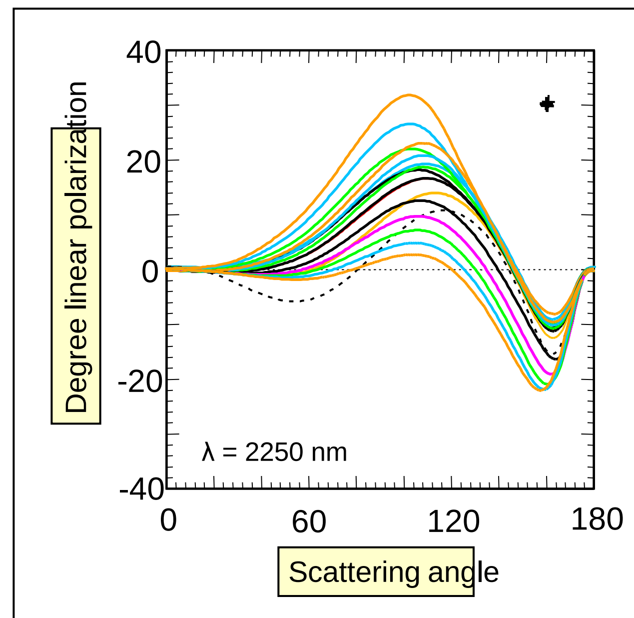
- Dust model
  - Derived from the data base constructed by Oleg Dubovik and co-workers



aspect ratio $\varepsilon' \equiv \frac{\text{major}}{\text{minor}}$

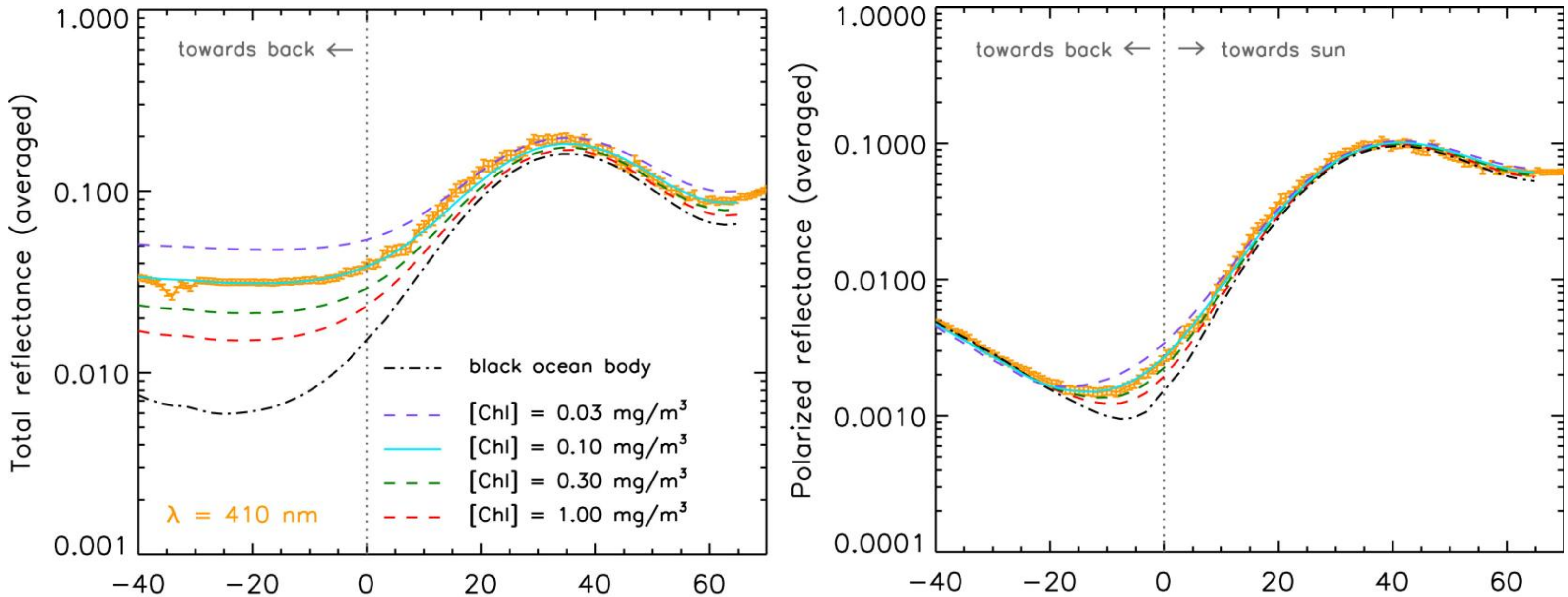






Aerosols

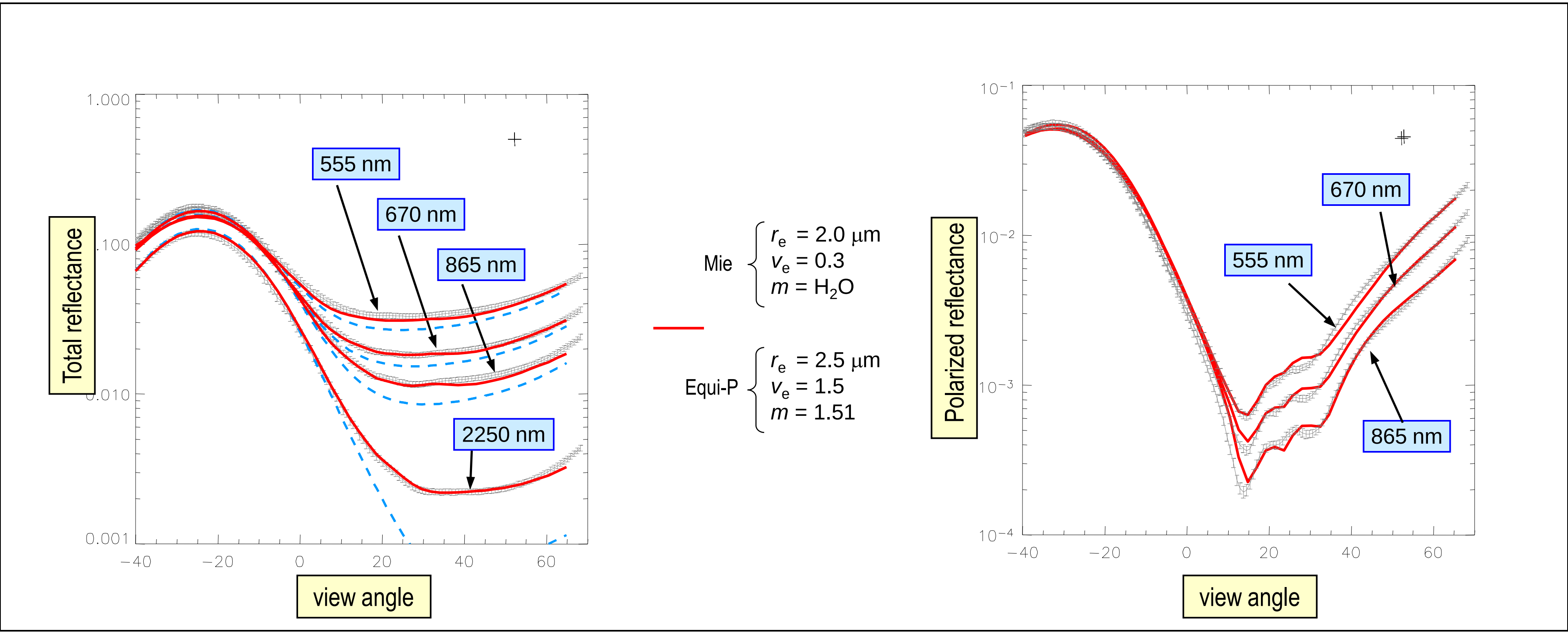
- Aerosols
  - Over oceans



- Oceans
  - Although polarized reflectance variations with Chlorophyll concentration are smaller than those in total reflectance it is still necessary to retrieve/specify Chlorophyll concentration as part of an aerosol retrieval in order to effectively use polarization measurements at 410-550 nm.
  - Uncertainties in CDOM absorption do not affect the polarized reflectance.
  - Glory will use MODIS Aqua [Chl] to define the lower boundary condition for aerosol retrievals

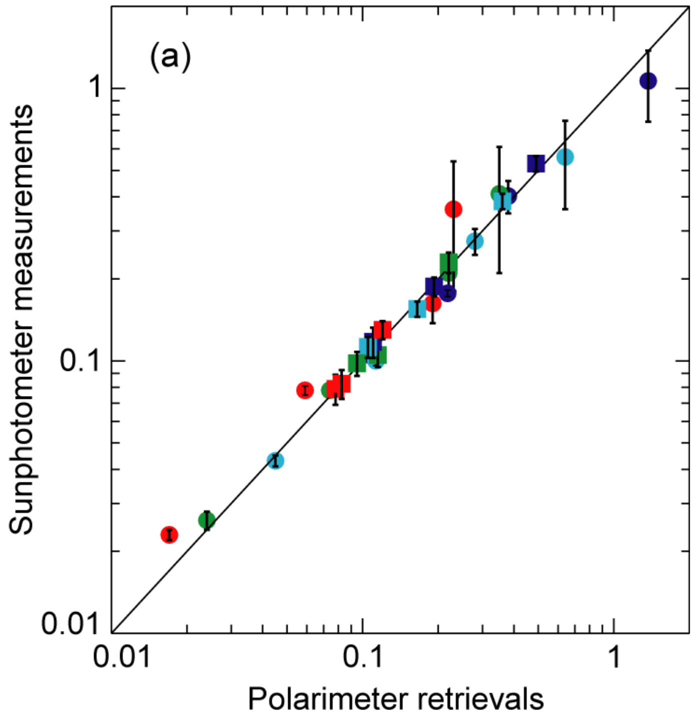
Aerosols

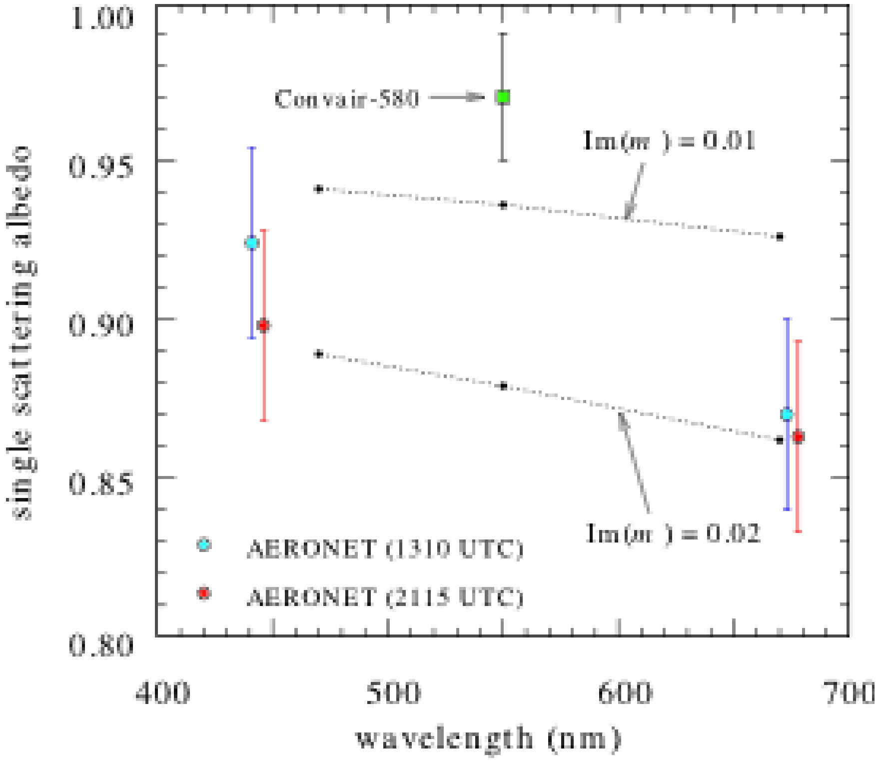
- Aerosols
  - Over oceans



- Observations over oceans have greater sensitivity to particle shape, because of a better constrained lower boundary condition for the total reflectance observations
- Have been used to evaluate dust models

Aerosols

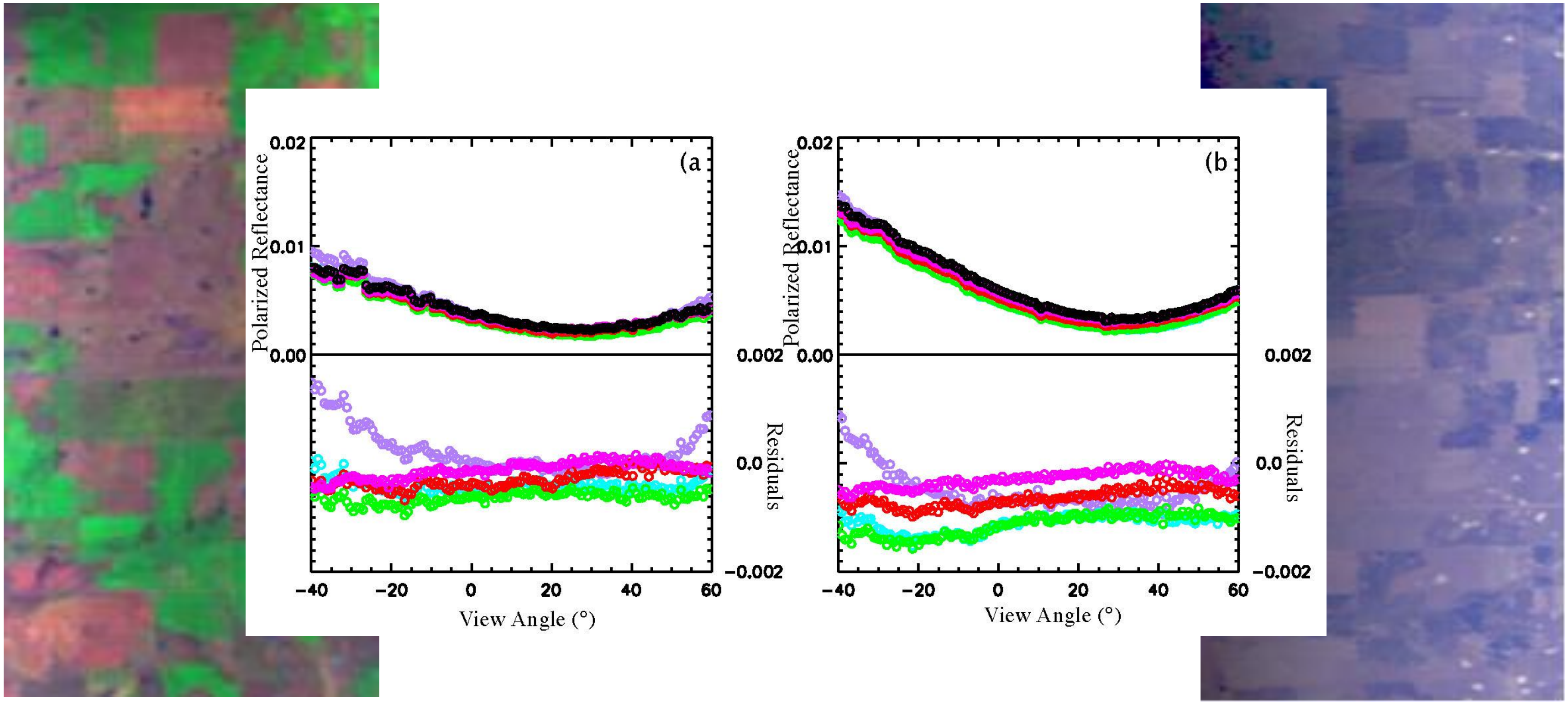




- Retrieved spectral optical depths agree well with ground-based sunphotometers
- Single scattering albedo and its spectral variation are within the range given by other sources (surface - AERONET and in situ - CV580)

Aerosols

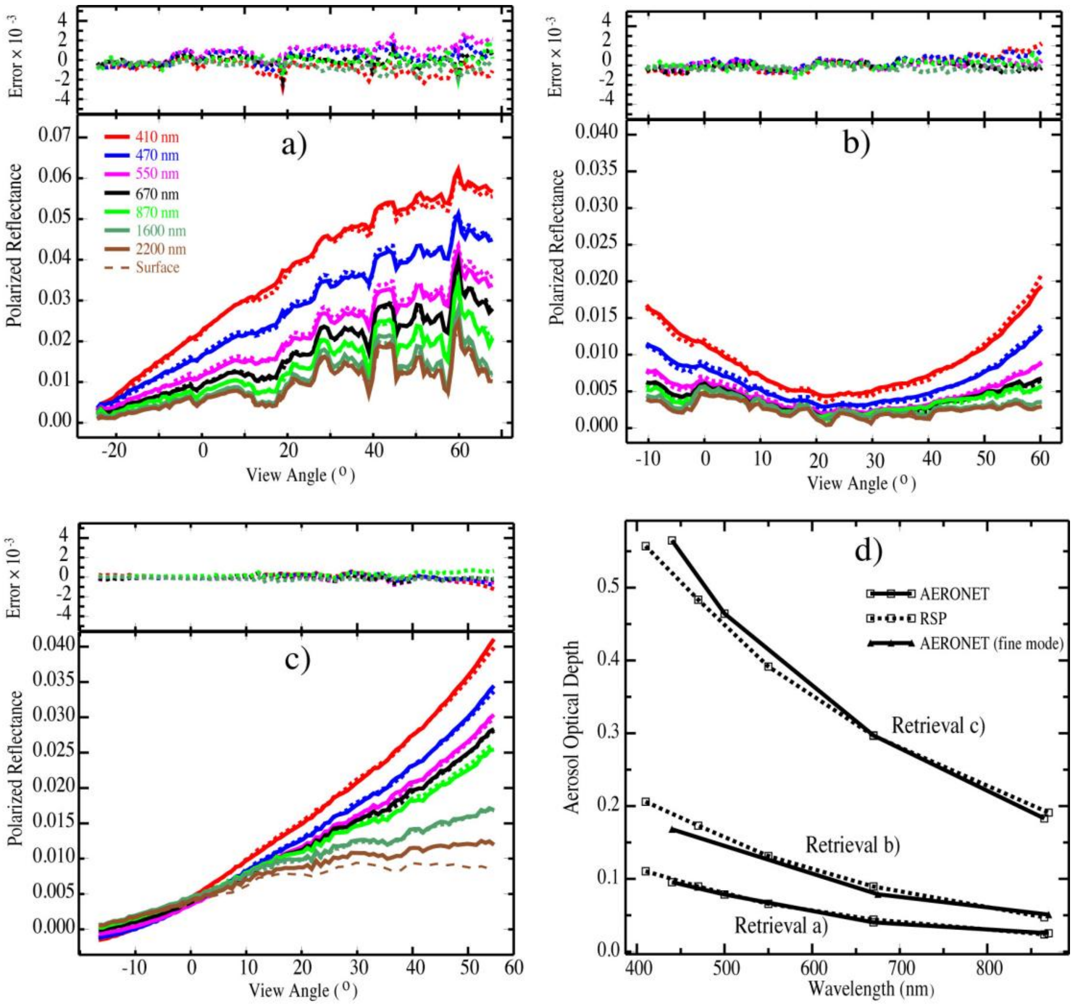
- Aerosols
  - Over land



- The polarized reflectance of land surfaces is grey. This means that:
  - Polarization is good for atmospheric remote sensing over land
  - Intensity is good for characterization of surface state (e.g. LAI)
    - a) Soy/Winter wheat
    - b) Bare soil

Aerosols

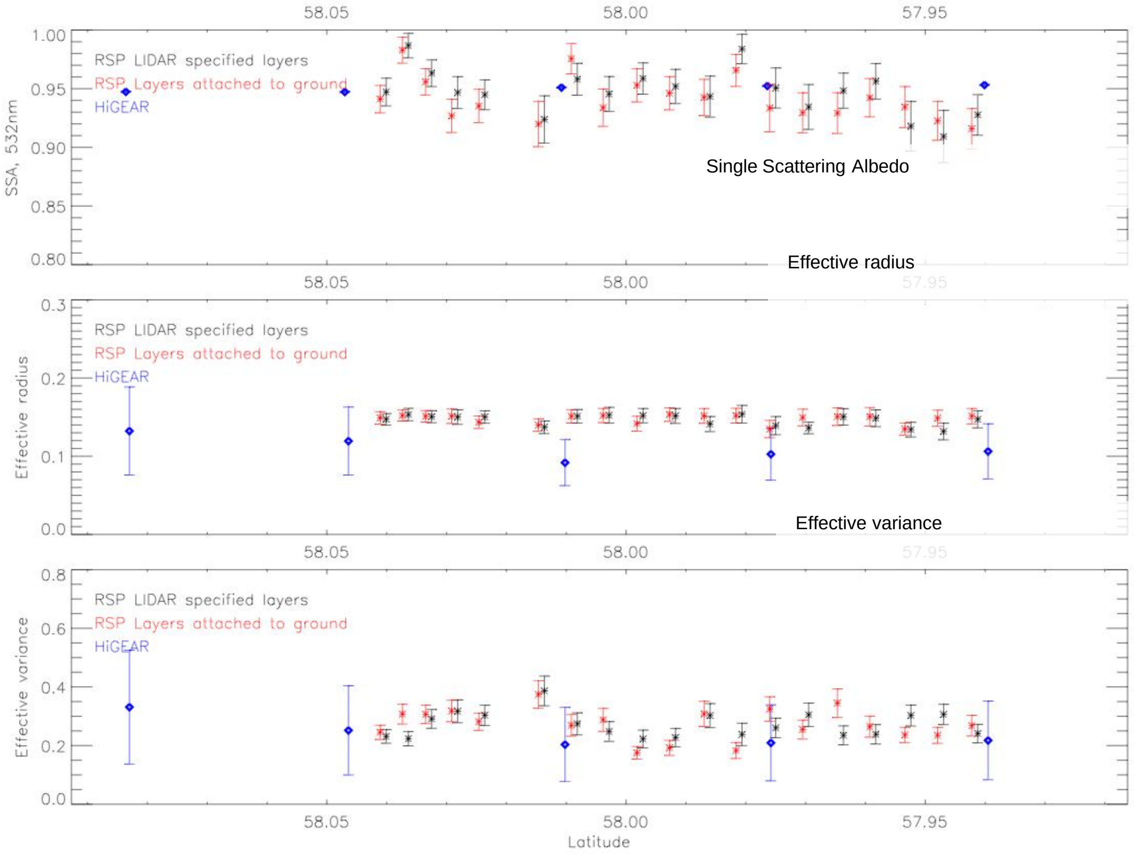
- Aerosols
  - Over land



- Polarization is sensitive to the aerosol load over land, even over urban areas (c, Mexico City)
- Not only can the aerosol burden be identified, but the spectral and angular signature in the polarized reflectance is sensitive to the complex refractive index (1.54 + *i* 0.027) and the single scattering albedo (0.865)
- Retrieved spectral optical depths agree well with ground-based sunphotometers

Aerosols

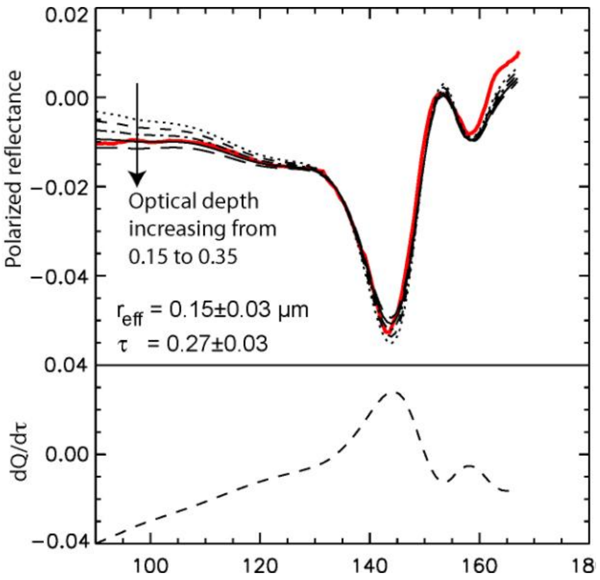
- Aerosols
  - Over land

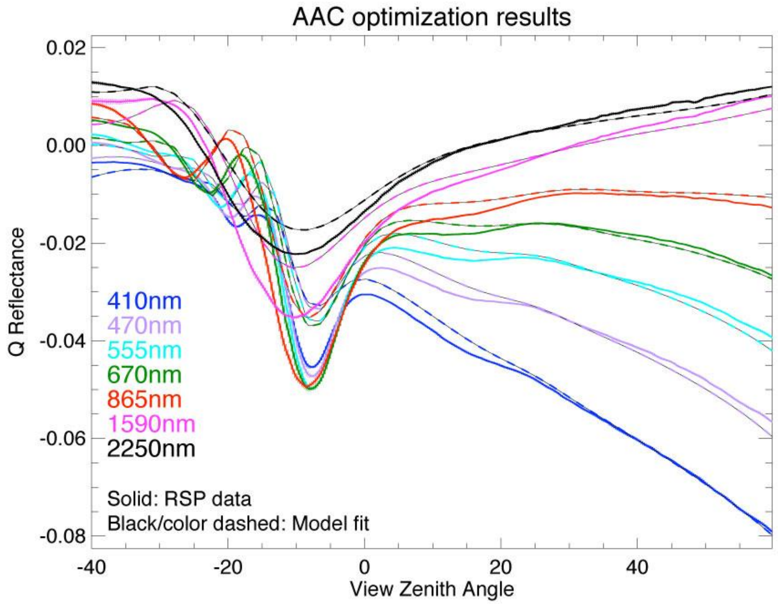


- More recent retrievals over land during ARCTAS provided good in situ intercomparisons between NASA P-3 and RSP on the NASA Langley Research Center B200

Aerosols

- Aerosols
  - Over clouds
  - Aerosols above cloud can be retrieved from NIR spectral bands in conjunction with visible/UV bands
  - Coarse mode retrieval above clouds is poor

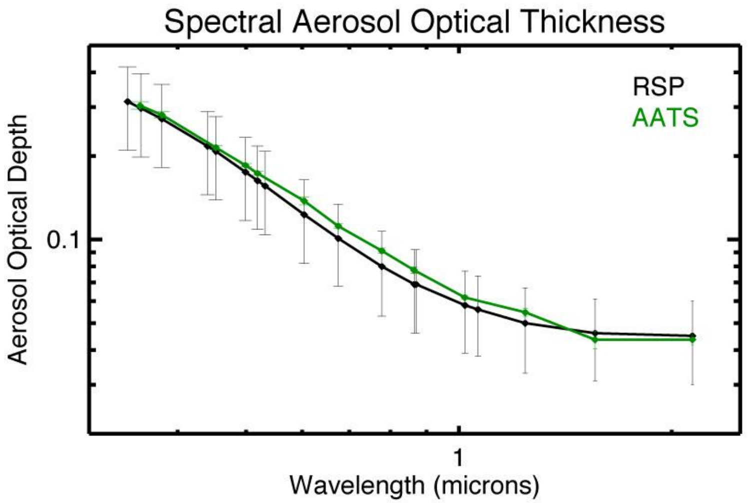


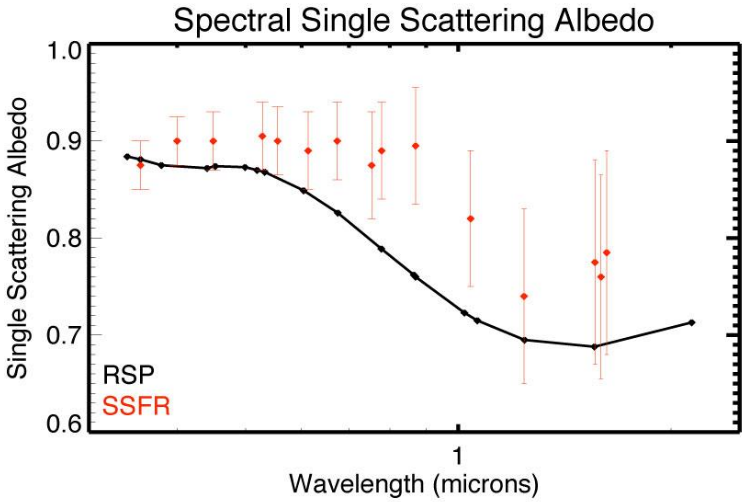


- Rainbow magnitude may exhibit three-dimensional effects that limit the use of the rainbow for the determination absorption

Aerosols

- Aerosols
  - Over clouds





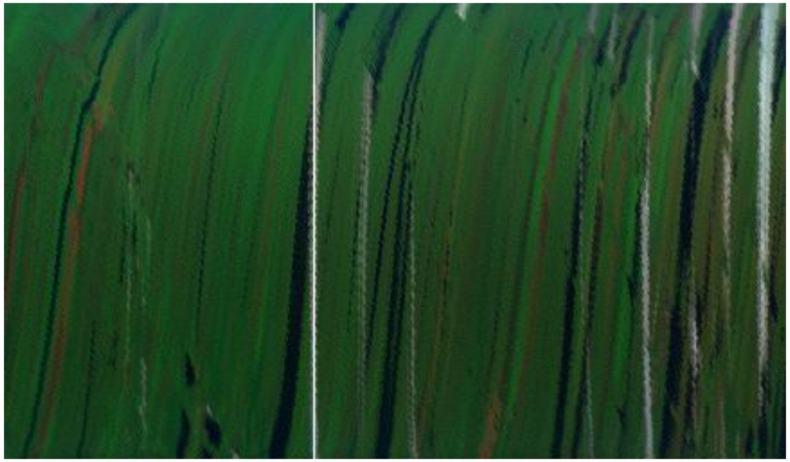
- Spectral optical depths agree well with AATS-14 measurements (Redeman *et al.* 2010)
- Retrieved single-scattering albedo has large uncertainties, but is broadly consistent with SSFR estimates (Bergstrom *et al.* 2010)

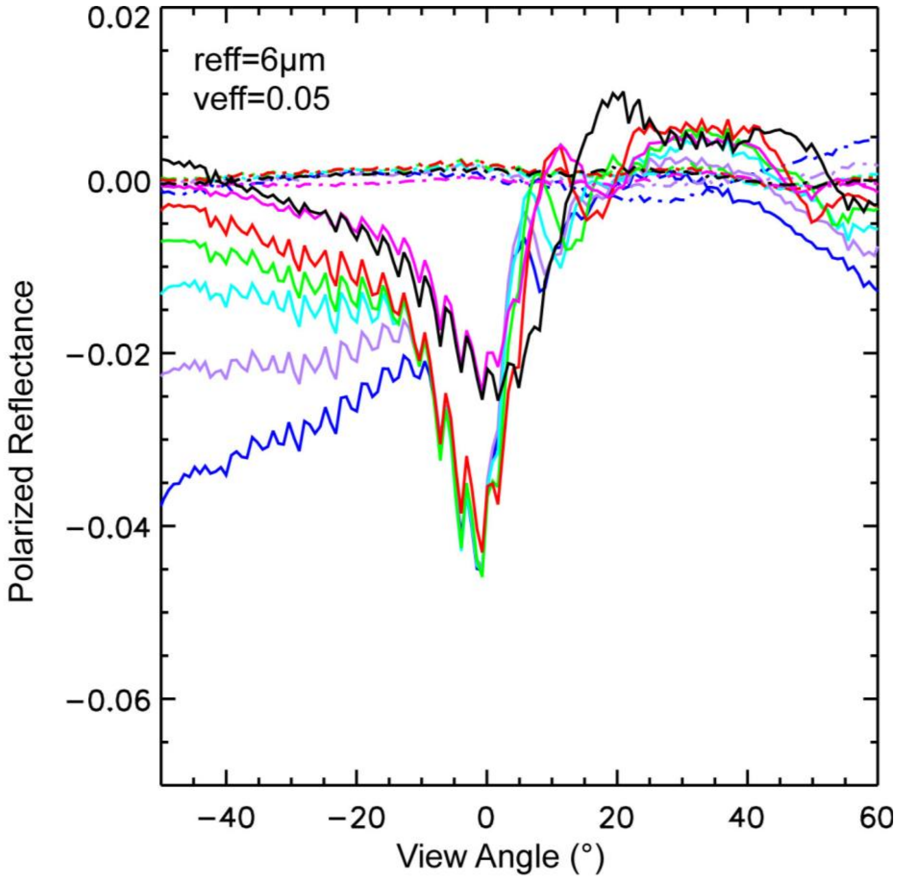
Clouds

- Clouds
  - Products are cloud fraction and for:
    - Water clouds
      - Cloud top pressure, effective radius and variance
      - Cloud optical depth
      - Cloud bulk effective radius (absorbing band method)
    - Ice clouds
      - Cloud top pressure, aspect ratio, roughness
      - Cloud optical depth
      - Cloud bulk effective radius (absorbing band method)

Clouds

- Water clouds





- Even popcorn cumuli have a distinctive rainbow.

- Stokes parameter Q in the plane of scattering is primarily determined by the Mie phase function (single scattering).

- Stokes parameter U is an order of magnitude smaller than Q.

Clouds

Total reflectance:

$$R(\theta) = \frac{\pi I(\theta)}{\mu_s I_0}$$

Polarized reflectance in scattering plane:

$$R_Q(\theta) = -\frac{\pi Q(\theta)}{\mu_s I_0}$$

I_0 - TOA irradiance, μ_s - cosine of SZA, θ - scattering angle.

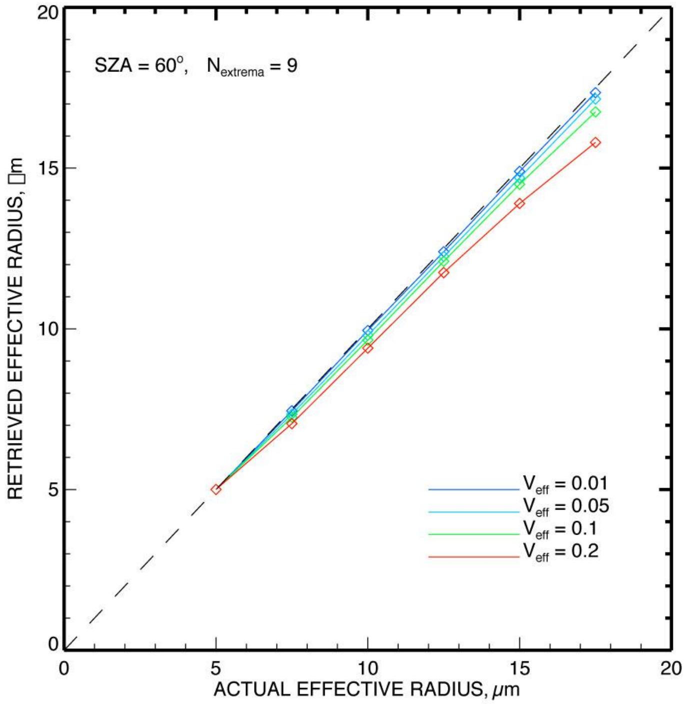
The fit:

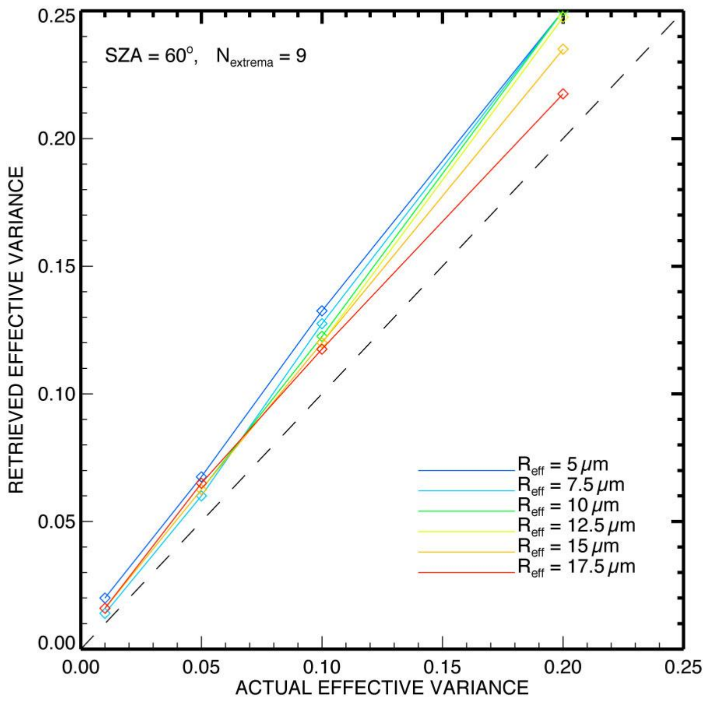
$$R_Q(\theta) = aP_{12}{}^{(Mie)}(\theta, r_{eff}, v_{eff}) + b\theta + c$$

The phase matrix elements $P_{12}{}^{(Mie)}$ are computed for a grid of effective radii and variances assuming a Gamma size distribution. Parameters a, b, and c account for the effects of multiple and Rayleigh scattering.

Clouds

- Water clouds
  - Other retrievals use exact 1-D RT
  - Cloud top particle size estimate just used Mie phase function

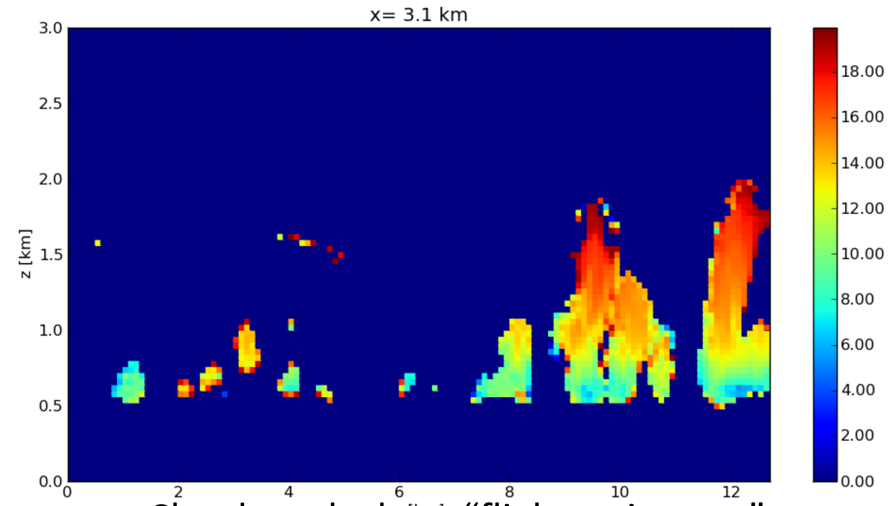


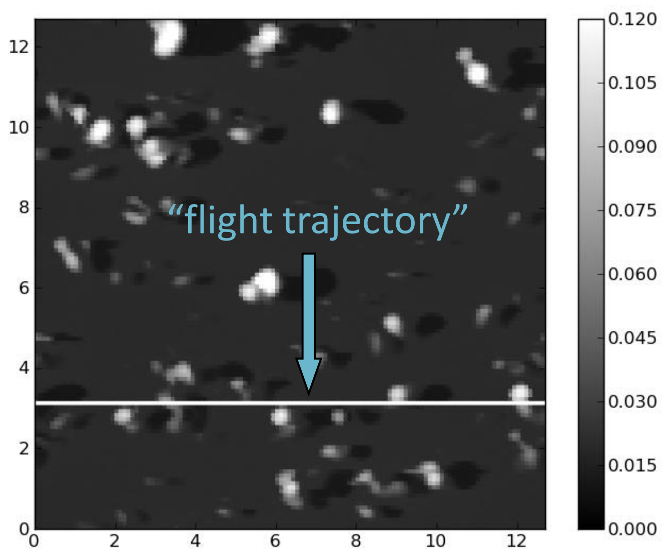


- Acceptable size bias that increases with effective variance.
- Effective variance bias that is lower for large particle sizes.

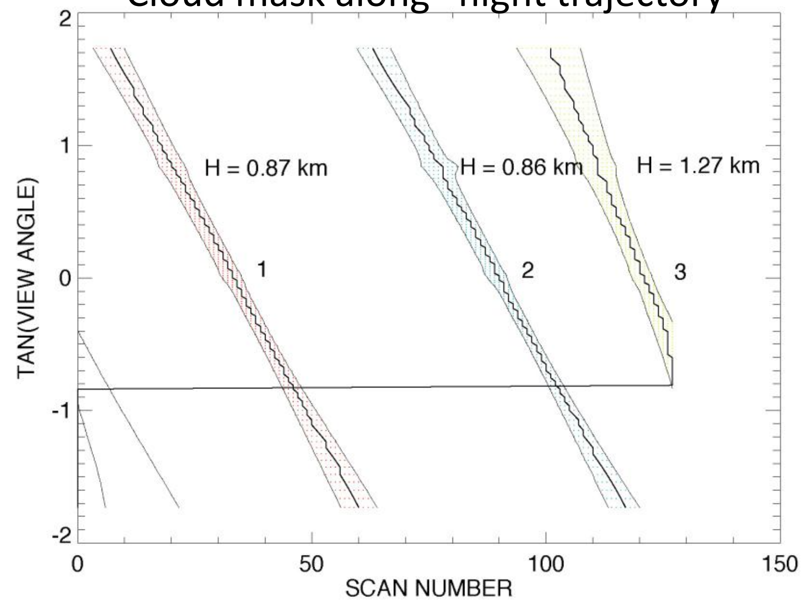
Clouds

- Water clouds
  - Test for 3D effects
- Calculation using **MYSTIC** (Monte Carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres, Emde et al. 2009)
- Applied to realistic cloud fields generated by microphysical simulations (LES for RICO field campaign by A. Ackerman)
  -



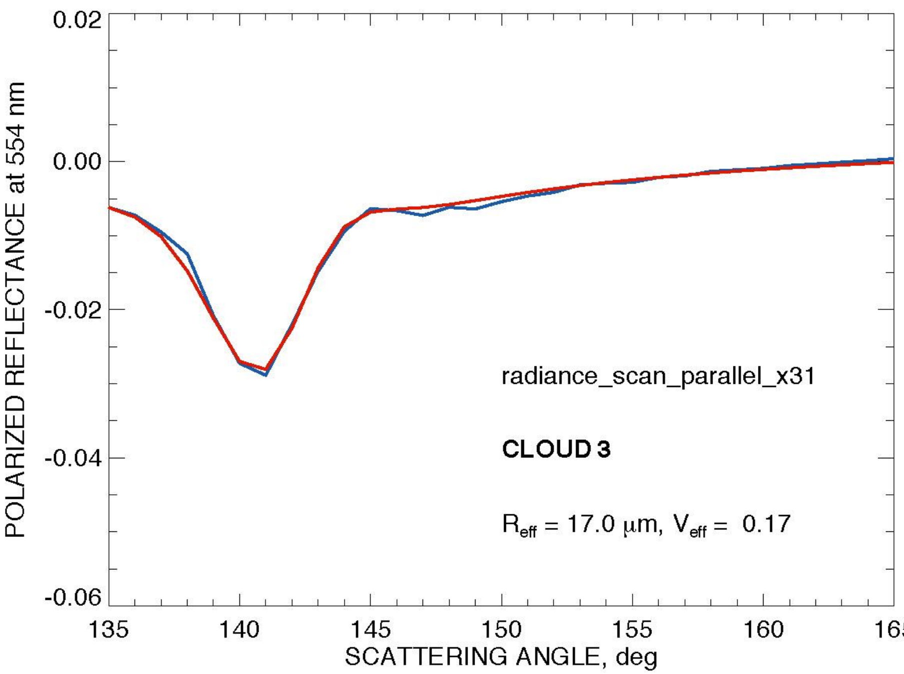


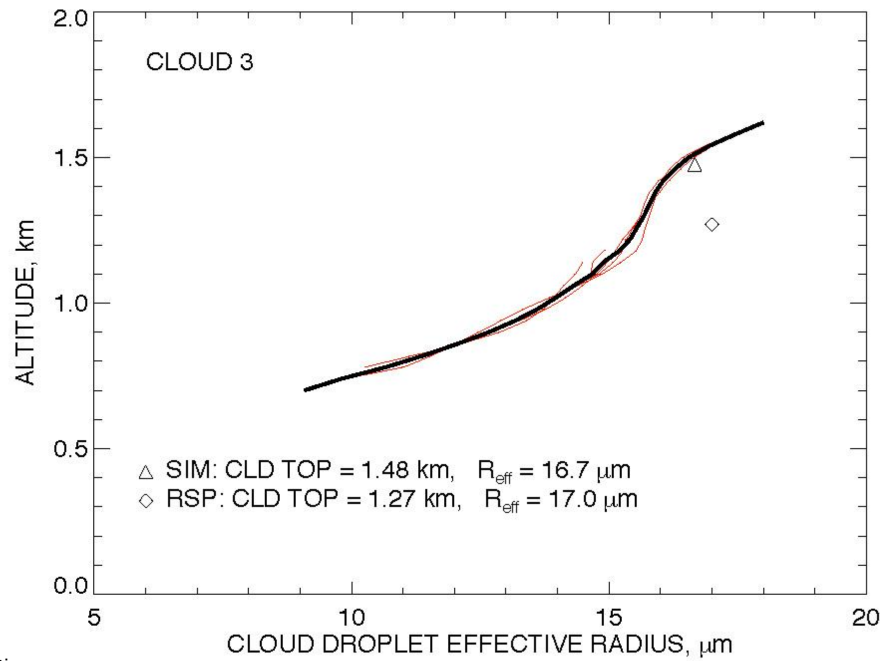
Cloud mask along “flight trajectory”



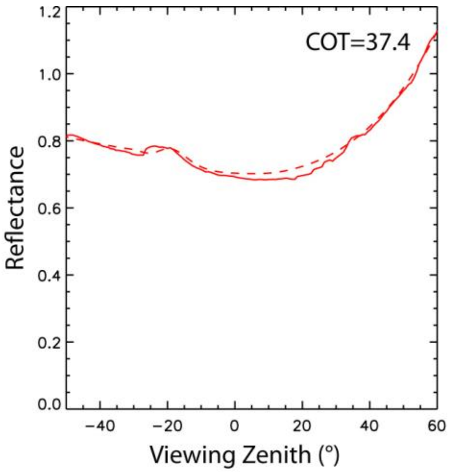
Clouds

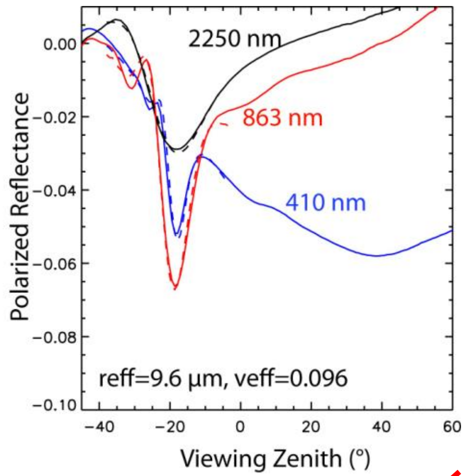
- Water clouds
  - Test for 3D effects
    - No obvious impact of 3D effects in droplet effective radius retrievals (<0.5 µm)
    - Increased effective variance compared with Monte Carlo for some retrievals (~0.05)



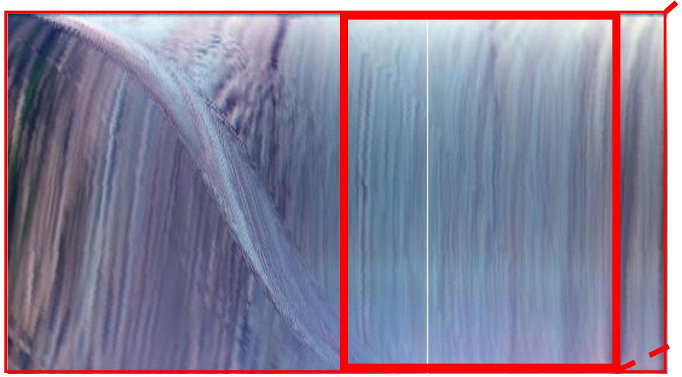


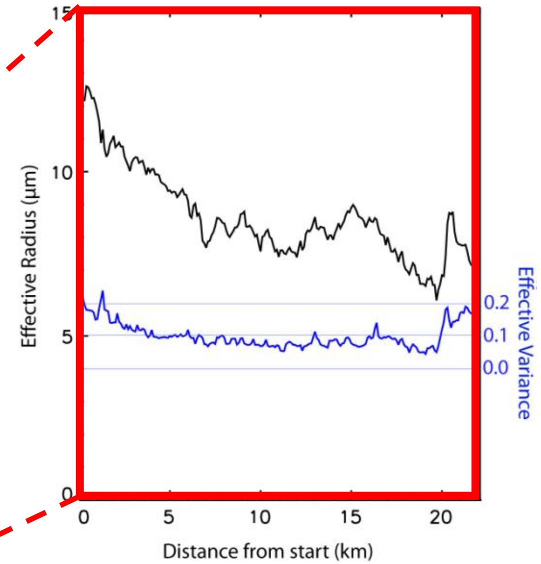
Clouds





- Water clouds

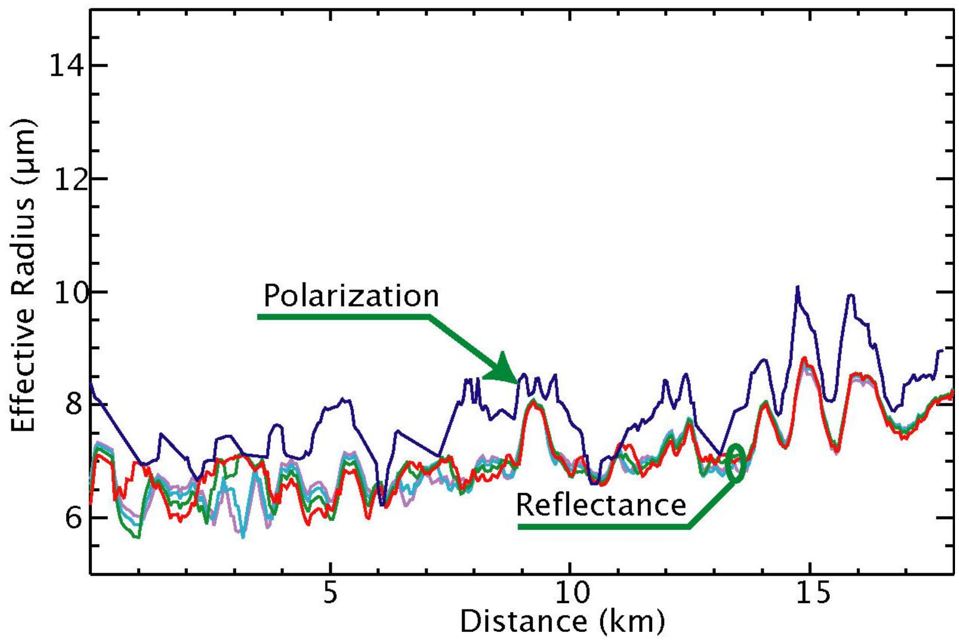


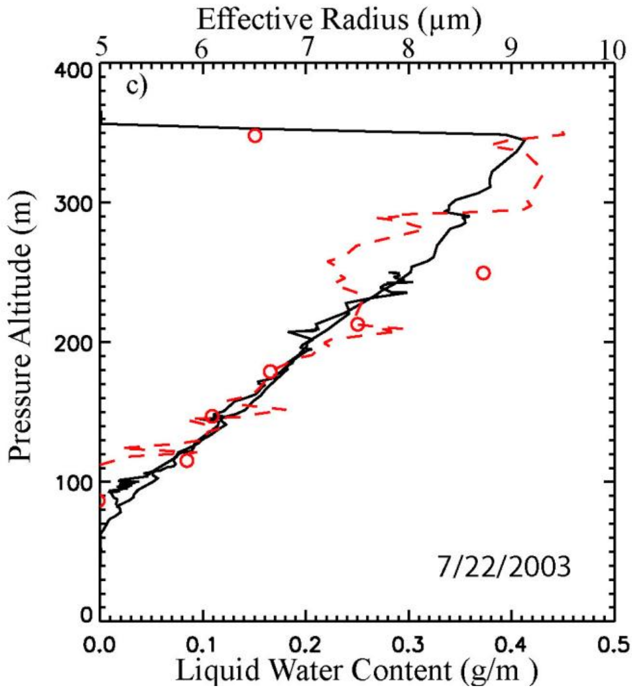


- Cloud optical depth determined from reflectance. Generally find good consistency across multiple views.
- Cloud droplet size distribution determined from structure of rainbow in multiple bands

Clouds

- Water clouds

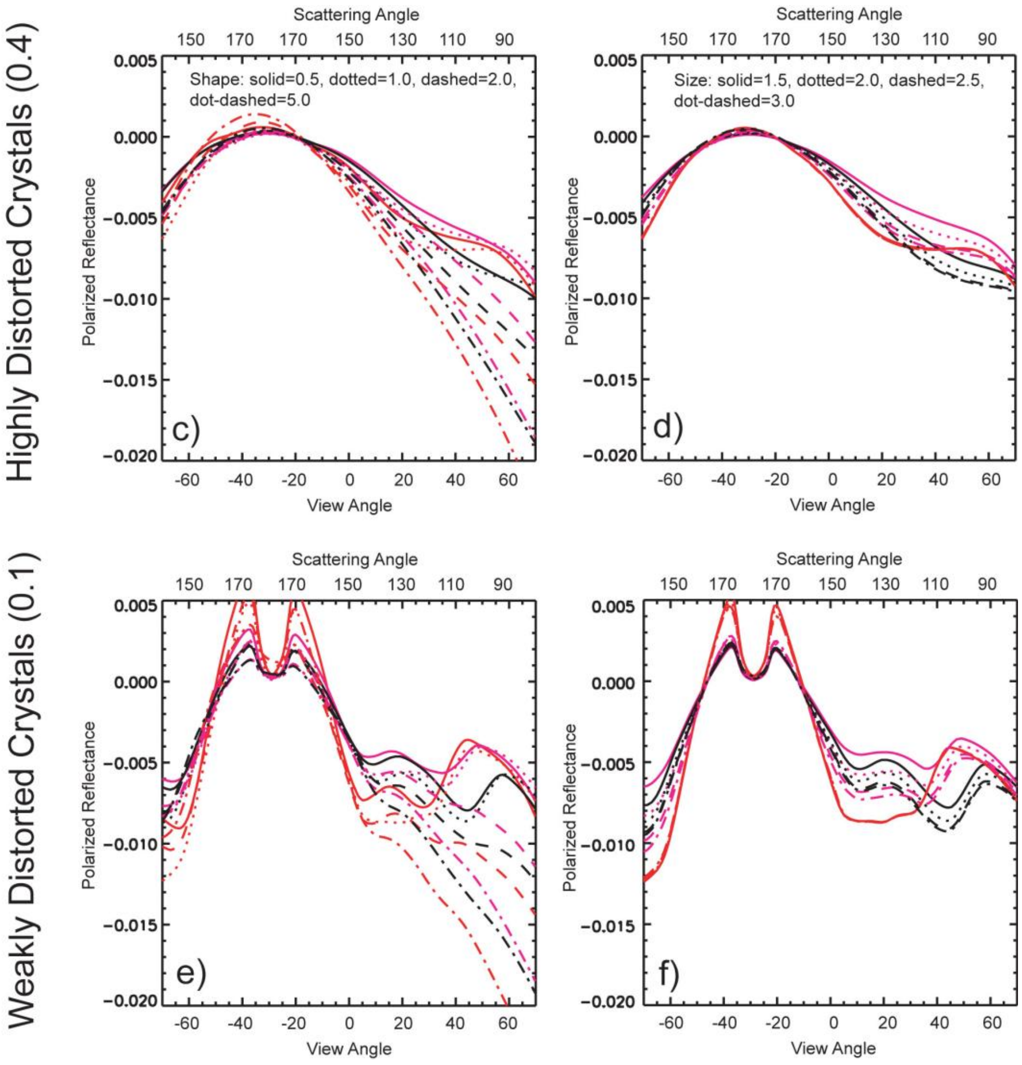




- Cloud size retrievals for polarization and absorbing band method generally consistent given cloud vertical structure for stratocumulus clouds.

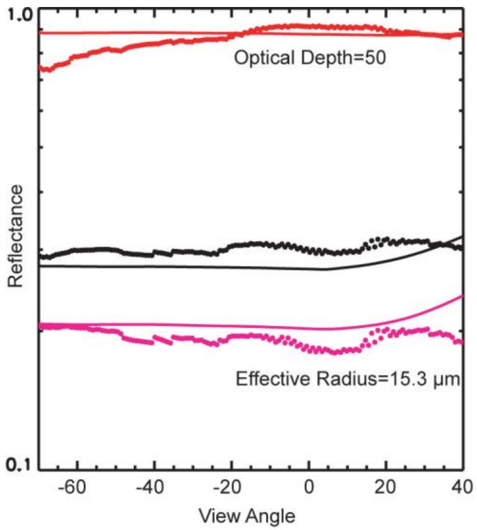
Clouds

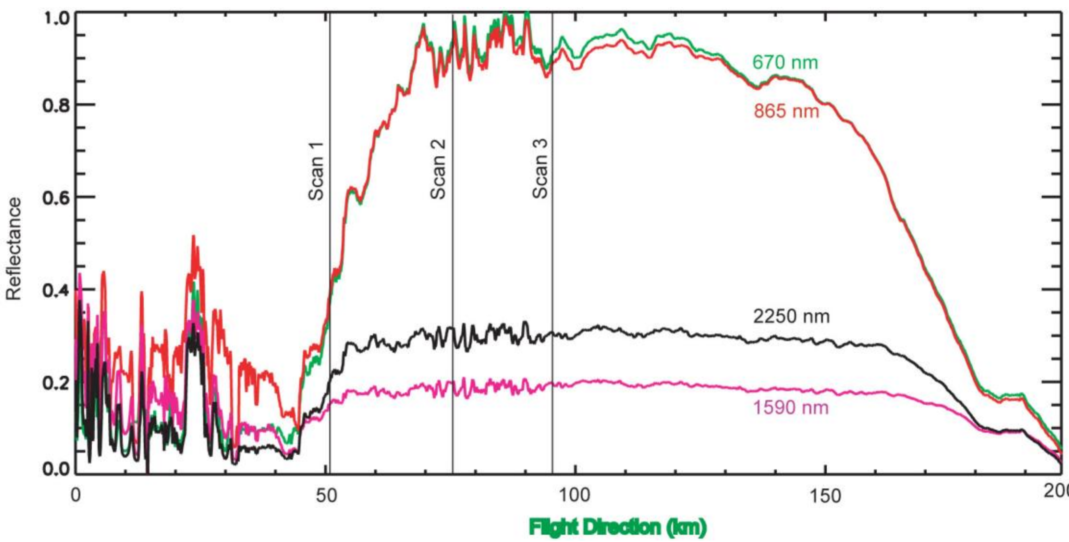
- Ice clouds
  - Aspect ratio and roughness/distortion dominate the behavior of polarized reflectance
  - Size plays a secondary role
  - Ice crystal model used has aspect ratios covering (0.5) plates to columns (5), pristine and distorted with size range of 10-500 µm



Clouds

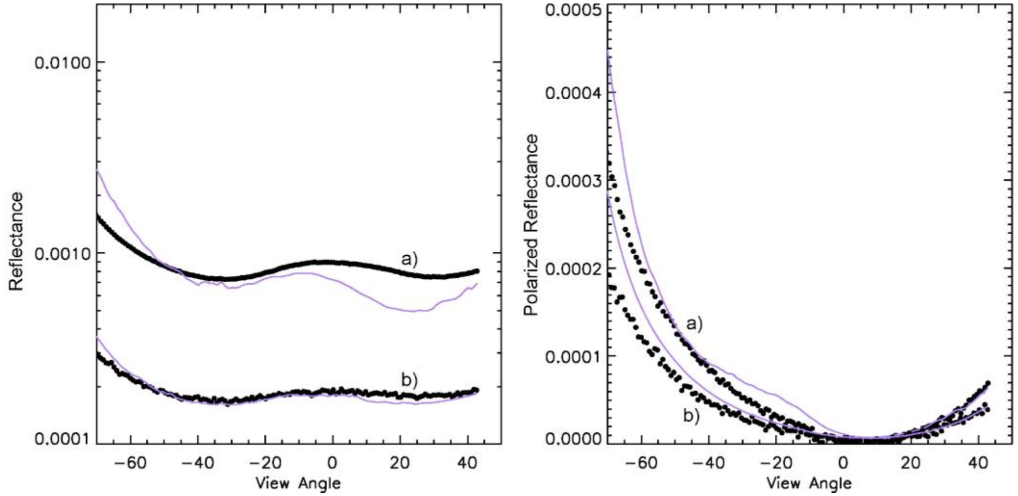
- Ice clouds
  - Aspect ratio and roughness/distortion selected from polarized reflectance observations
  - Expected vertical structure with smaller ice particles at top of cloud and larger ice particles at the bottom should not show the biases seen here for a joint fit of a 865, 1590 and 2250 nm using a homogeneous ice cloud layer.
  - Retrievals will be provided separately for each absorbing band (1610 and 2250 nm)



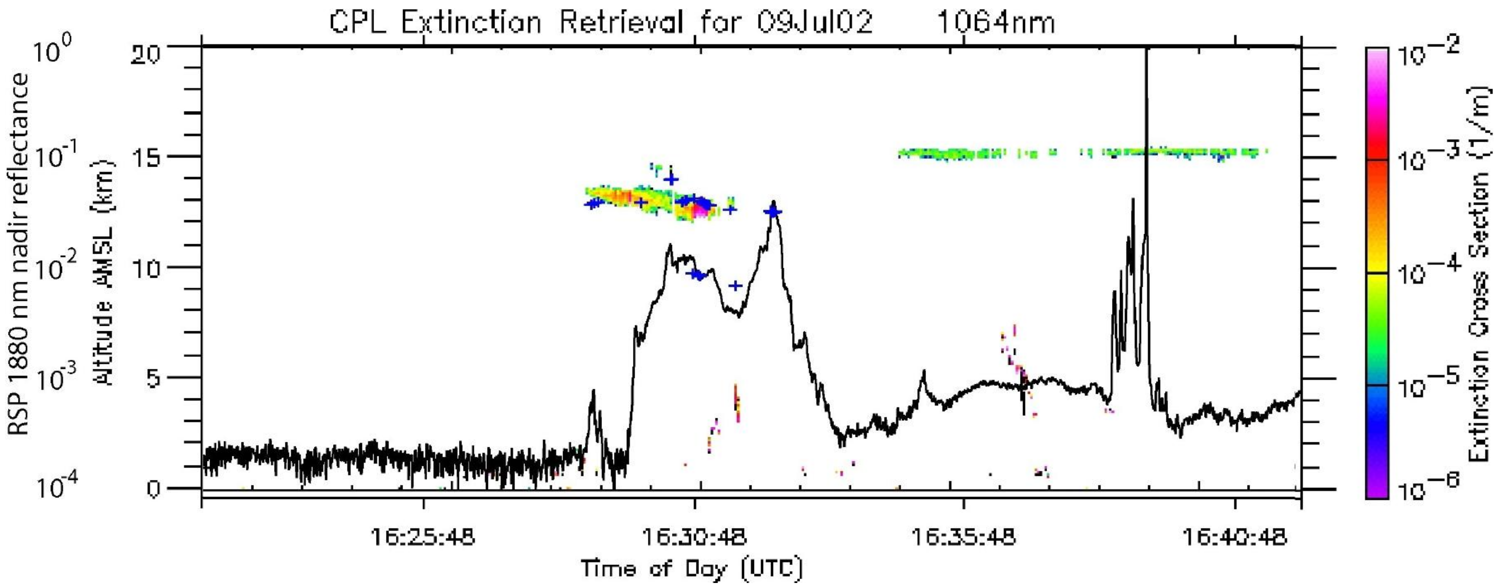


Clouds

- Ice clouds
  - Thin cirrus



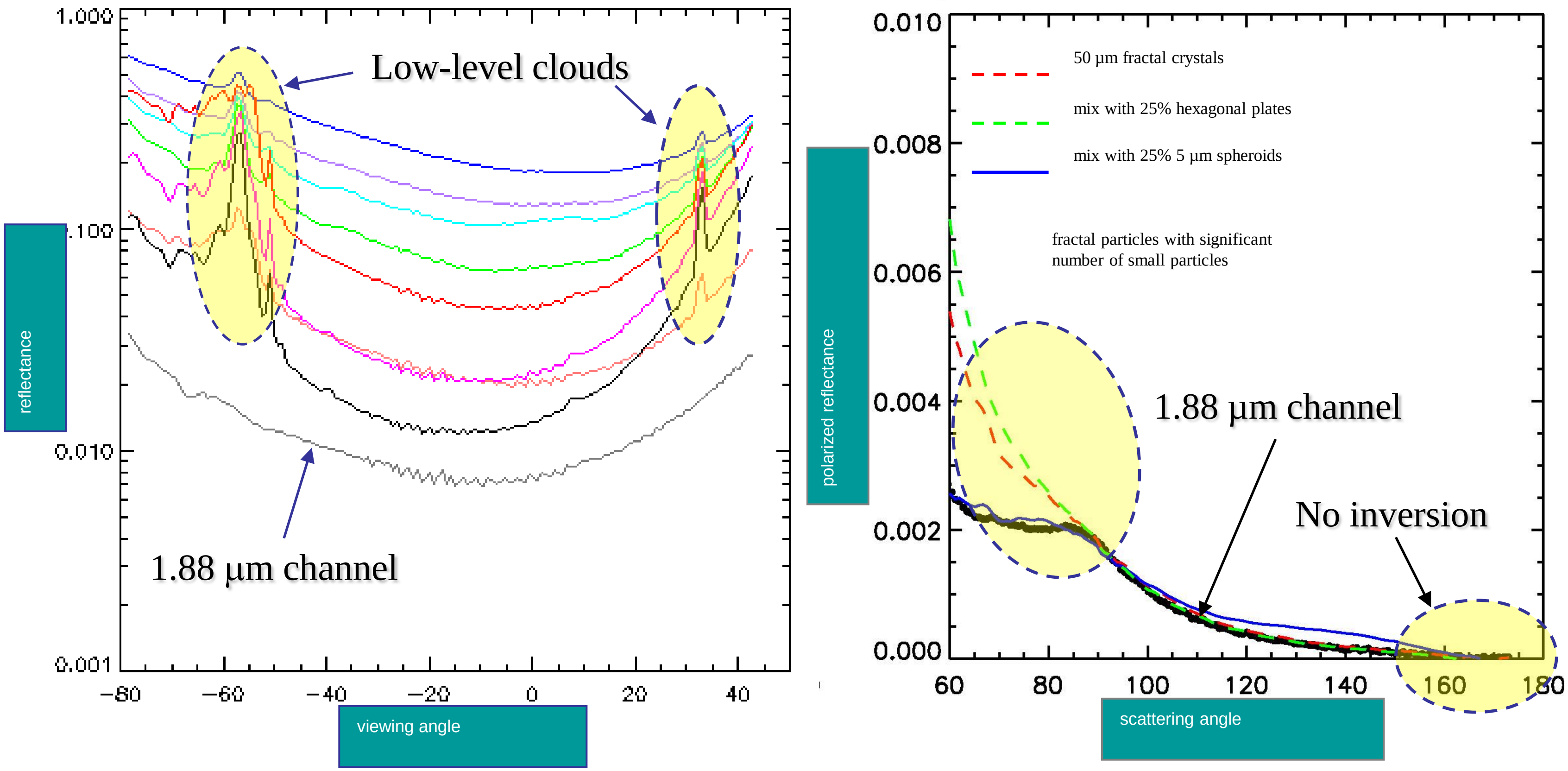
- a) COD=0.007 and r_{eff}=20 μm size assuming a fractal shape.
- b) Clear skies with a Rayleigh optical depth of 0.00025.
- c) Cloud top height uncertainty increases for clouds with optical depth less than 1.0. i.e. No cloud top heights for sub-visible cirrus.



Clouds

- Ice clouds
  - Thin cirrus

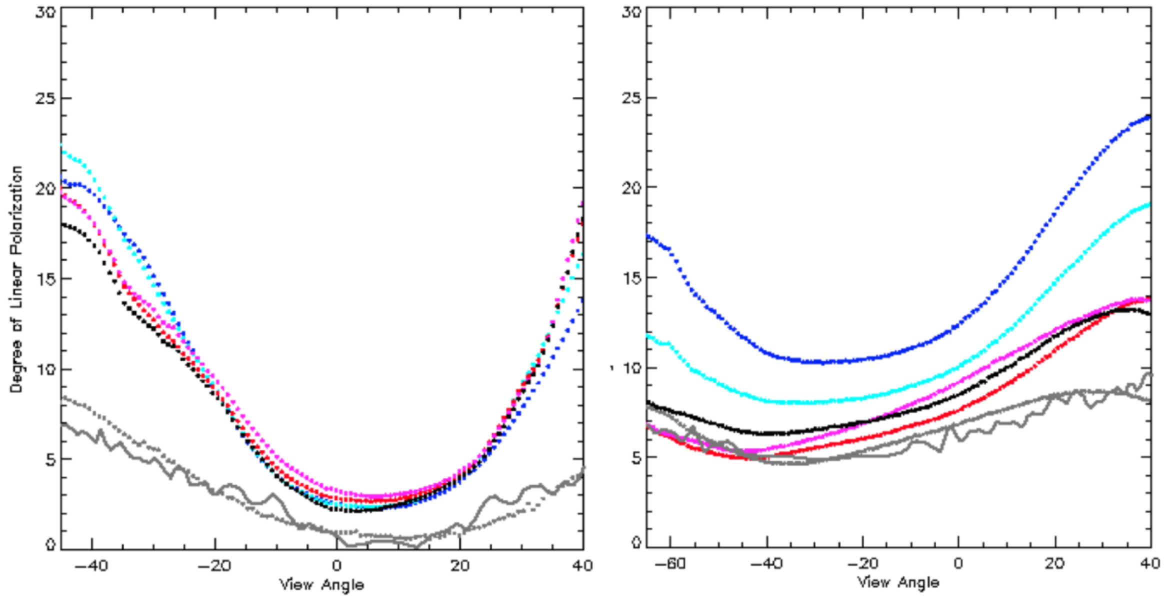
➢ Optical depth (0.1) & size distribution in agreement with lidar & in situ data



APS: 1.38 µm - Gao & Goetz (1994), *Geophys. Res. Lett.* **21**, 2023-2026

Clouds

- Ice clouds



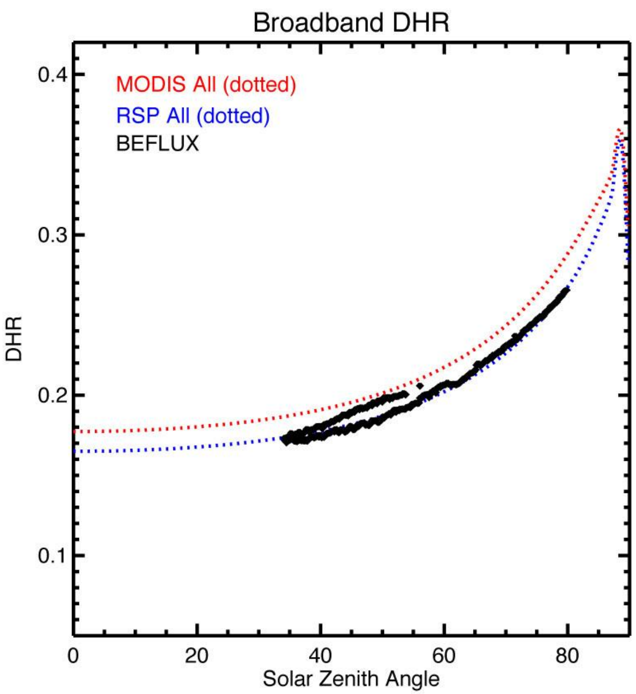
- Limited data set for evaluation of phase matrix models, especially for thin cirrus.
  - Example here is for fit of fractal model to thing cirrus observations during Crystal-Face
  - Initial Glory ice cloud evaluations will focus on whether other models such as IHM (Labonnote et al.) and the new MODIS Collection 6 ice models from Bryan Baum and Ping Yang that have rough ice and small droxtals provide a better match to the observed polarization.

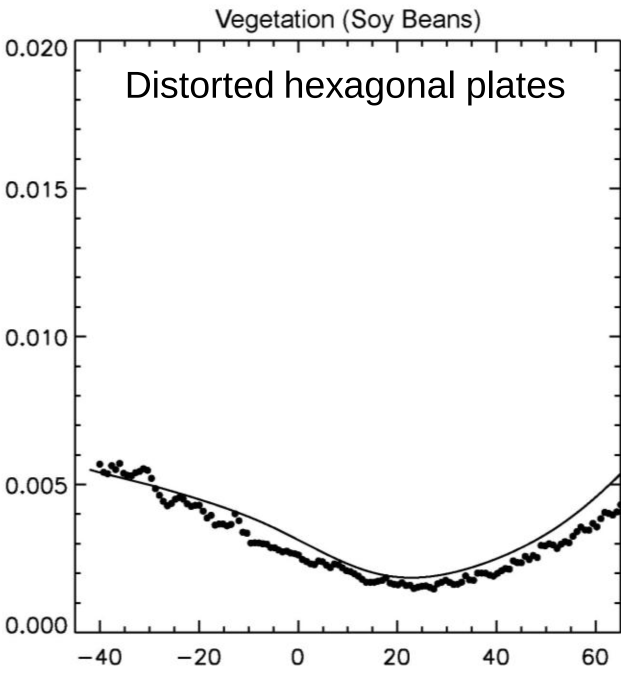
Surface BRDF

- Surface BRDF
  - Kernel model (Ross-thick, Li-thin as in MODIS) used to model surface reflectance
  - Scaled vegetated surface model is baseline for polarized lower boundary condition.
  - Products:
    - Kernel weights and scale factor for polarized surface reflectance model for each APS window spectral band
    - Weights for broad band DHR model (integral of kernel models)

Surface BRDF

- Surface BRDF
  - Limited existing validation of broadband surface albedo shows good agreement with surface observations
  - In some cases the standard models for surface polarized reflectance (Bréon, Deschamps, Vanderbilt) are not adequate
    - If residuals at 2250 nm are large for thin aerosols other phase functions such as the one shown on the right will be substituted for an isotropic Fresnel model.





Glory Products- Summary

- Cloud Mask
  - Use MODIS and CALIPSO masks
  - Generate cloud camera and APS cloud masks
- Water Vapor
  - Total column water vapor
  - In cloud/below cloud top estimate when cloud present
- Aerosols
  - Optical depth, effective radius and variance and complex spectral index for two modes with retrieval uncertainties
  - Retrievals performed for partially cloud filled pixels for accumulation mode using only polarized reflectances
  - Retrievals performed or aerosols above clouds when cloud top pressure estimate disagrees with CALIPSO cloud top

Glory Products- Summary

- Clouds
  - Water clouds
    - Cloud top pressure, effective radius and variance
    - Cloud optical depth and bulk effective radius (absorbing method)
  - Ice clouds
    - Cloud top pressure, aspect ratio, roughness
    - Cloud optical depth and bulk effective radius (absorbing method)
- Surface BRDF
  - Ambrals kernel model – same as MODIS land surface product together with broad band model
  - Polarized BRDF scale factor for soil/vegetated surface model
  - New polarized surface BRDF model if required
    - Will only be introduced if residuals for low aerosol loads are high

Glory Tools and Documents

- http://glory.giss.nasa.gov/aps/docs/
  - Is
    - ATBDs, spectral responses
  - Will be
    - Sample HDF-EOS files and user guides
- http://glory.giss.nasa.gov/aps/tools/
  - Will be
    - Vector radiative transfer code
    - Correlated *k*-distributions for the APS bands
    - Ice cloud model
    - Dust model
    - Tables of polarized radiative transfer results
    - Retrieval algorithms

Glory Tools

- Vector radiative transfer code
  - This is a vector doubling/adding code based on Hansen and Travis (1974) but including the speed and accuracy improvements identified in de Haan et al (1987)
- To calculate radiative perturbations need

$$\mathbf{I}'' = \mathbf{I} - \int_0^{\tau_c} \mathbf{G}(0,\tau)\Delta\mathbf{L}(\tau)\mathbf{G}(\tau,0)\mathbf{S}\,d\tau + O(\Delta^2).$$

- Internal fields of doubling adding codes provide the required Green's functions for the multiple viewing angles needed for observation such as those from MISR, POLDER and APS.
- Internal fields at 2^N-1 internal points can be obtained for any homogeneous layer making up a vertically inhomogeneous atmosphere just by saving the last N adding results for that layer.
- Perturbations to number concentrations do not require any internal resolutions of a layer.
- Calculating internal fields for an internal source (as required for the calculation of perturbations for aircraft observations) is straightforward.

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http://glory.giss.nasa.gov/

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